A Multi-Objective Two-Echelon Vehicle Routing Problem. An Urban Goods Movement Approach for Smart City Logistics

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***Abstract*—Current trends of urbanization and growing economies bring with them rising levels of traffic congestion and city governments must recur to new strategies to deal with such problems. Multi-level distribution is an already-known strategy employed by businesses, and the classic formulation of the *Two-Echelon Vehicle Routing Problem* (2E-VRP) reflects the perspective of a single provider, without regarding the routing decisions of other parties. The lack of coordination between providers executing their individual schedules and, consequently, the lack of a holistic approach to urban traffic may cause further problems. Additionally, the various stakeholders (government, businesses, residents) may have conflicting objectives. The main contribution of this paper is a first-time multi-objective formulation of the multi-provider (or multi-commodity) heterogeneous vehicle 2E-VRP, from a city government perspective within an Urban Goods Movement context, demonstrating with didactic examples the potential benefit of this approach to all parties involved, simultaneously considering potentially conflicting objectives.**

***Index Terms*—Two-Echelon Vehicle Routing Problem, Multi-Objective Optimization, Urban Goods Movement, Smart City Logistics, City Distribution Centers**

1. Introduction

Current trends of urbanization and growing economies bring with them rising levels of traffic congestion in cities, especially if the potential development of urban infrastructure is limited, due to costs, popular resistance to large-scale construction projects, or natural accidents such as mountains or rivers (e.g. Asuncion). If the infrastructure cannot be adequately expanded to absorb the rise in traffic, national and city governments must recur to new strategies that optimize vehicle flow to deal with such problems [1]. One possible strategy, already employed by individual businesses and transportation companies, is multi-level distribution of urban goods. This work proposes a model using the Two-Echelon Vehicle Routing Problem, or 2E-VRP, in order to design a multi-level distribution strategy from a holistic perspective, useful for city governments.

The classic *Vehicle Routing Problem* (VRP) consists in serving a number of customers located at distinct geographic points, and to do so a central depot and a fleet of vehicles are provided. To solve this problem, routes must be assigned, meaning ordered sets of clients, to the vehicles in the most optimal way possible, usually striving for the minimal time or travel cost to cover the demand [2].

Under certain circumstances there may be reasons to not serve the clients directly from the central depot but through intermediate points, generally known as *City Distribution Centers* (CDCs) or satellites. This can happen for example if there are large trucks that leave the central depot but should not (or are even forbidden to) enter a certain zone, such as the inner city, and CDCs are set up outside or on the edges of these restricted areas where the large trucks unload their freight and smaller vehicles deliver the freight to the customers within the areas [3]. In this case, it can be said that there are two layers or echelons of vehicles and locations, giving rise to the 2E-VRP.

Significant research has been focused on the 2E-VRP, most notably by Gonzalez-Feliu in [4]. The most studied approach for the 2E-VRP considers a multi-level distribution scenario for products of a single provider [5], [6]. However, each provider in a city solving its own routing problem separately and independently of the others could result in suboptimal solutions for the city as a whole. Furthermore, a city government may have the goal of reducing traffic congestion and pollution, requiring a holistic perspective of *Urban Goods Movement* (UGM) [1], [7], considering all providers contributing to city traffic.

For this reason, one can consider the 2E-VRP as a multi-level distribution scenario with multiple providers and products, also known as multi-commodity [8]. This holistic approach that reflects the diverse nature of urban traffic is better adapted to tackle the global problem of urban traffic congestion. In this way, instead of solving several parallel 2E-VRP instances that are not aware of each other, one for each provider or product, a city government can unify these

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instances by having all (or several) providers share all (or several) CDCs, from where (possibly independent) smaller, greener second-echelon vehicles carry diverse freight to serve the demand of clients in the restricted area.

Additional challenges arise when adapting the 2E-VRP to the context of UGM, given the existence and participation of multiple stakeholders, e.g. the city government and businesses. The objectives of the different stakeholders will most likely be distinct and may be in conflict, such as businesses seeking to minimize cost, distance, and time of travel and delivery, and the city government seeking to minimize the number of freight vehicles in simultaneous transit during a given period in the considered area, or the pollution those vehicles produce. A viable solution may require a reasonable trade-off. This situation motivates us to consider a Multi-Objective formulation that attempts to simultaneously optimize several objective functions, presenting a Pareto set approximation to the decision makers [9].

When considering the traffic problems in major cities, such as Asuncion, Quito, or Guayaquil in the case of the authors, it may seem impossible or at least unfeasible to model the whole traffic of the entire urban landscape and apply the aforementioned strategy to the whole city in an attempt to reduce traffic congestion. However, inspired by the classic divide-and-conquer method used so often to solve large problem instances, the goal can be to reduce traffic congestion in just a relatively small area, such as part of the downtown of the city with heavy commercial activity. This area can be a restricted area or the second echelon, while the trips from providers to the CDCs set up on the edges of this area would be the first echelon.

The 2E-VRP is a generalization of the VRP which is known to be NP-hard [7] and it is therefore impossible to find the optimal solution in polynomial time. The difficulty is further raised considering the large amount of input parameters for the given problem, such as quantity of vehicles, customers and routes. For this reason, in this work the authors propose to design a meta-heuristic in order to solve the problem.

The remainder of this paper is structured as follows: in Section 2 the related research and the motivation for this work is addressed, and in Section 3 the proposed problem formulation is presented, followed by simple motivational examples in Section 4 to make the case for multi-commodity two-tiered distribution in city logistics, ending with the conclusion in Section 5.

2. Related Works and Motivation

To the best of the authors' knowledge, the first formal definition of the 2E-VRP is by Gonzalez-Feliu [4], specifically considering the *Two-Echelon Capacitated Vehicle Routing Problem* (2E-CVRP). Gonzalez-Feliu et al. [10] introduce the family of multi-echelon VRPs and present the 2E-CVRP. Other examples of contributions by Gonzalez-Feliu to the growing body of literature on the 2E-VRP and closely related topics include [11], where the main concepts of two-echelon distribution are presented via a systematic review, and [12] on the main concepts of multi-echelon distribution with cross-docks and a unified notation for the N-echelon location routing problem.

Cattaruzza et al. [1] briefly explore the well-known VRP in the context of multi-level distribution, defining CDCs and explaining the 2E-VRP as well as the *Two-Echelon Location Routing Problem* (2E-LRP). They identify the 2E-VRP as the most studied problem in multi-level distribution and lay out several common assumptions, such as a unique central depot. They also identify a number of articles that concern multi-level distribution. Of these, they refer to two articles in particular for complete surveys on two-level distribution systems [5], [6].

Gonzalez-Feliu [5] attempts to unify the concepts of multi-echelon distribution with cross-docks and the notation standards for cost optimization in order to provide a guide to researchers and practitioners. He first lists the main problems and methods found in the literature and subsequently presents the main concepts and standards of multi-echelon based vehicle routing optimization problems by applying a hybrid systematic analysis method combining a lexical and a meta-narrative analysis. A theoretical model and a classification of solution methods are also presented.

Cuda et al. [6] survey two-echelon routing problems providing an overview of two-echelon distribution systems. They consider three classes of problems: the 2E-LRP, the 2E-VRP, and the *Truck and Trailer Routing Problem* (TTRP). Regarding specifically 2E-VRP, the problem class is generally described and the 2E-CVRP, being the most studied problem of the class, is emphasized, followed by a review of the foremost papers tackling the problems of this class. The papers listed and summarized in [6] were selected for the literature overview in this work, resulting in 9 of the most relevant articles relating to 2E-VRP [7], [13], [14], [15], [16], [17], [18], [19], [20] studied for this section, which are described next.

Crainic et al. present three separate but related papers on solving the 2E-VRP with (meta)heuristics based on separating the first and second level routing problems and solving iteratively the two resulting routing subproblems, while adjusting the satellite workloads linking them. Their objective is to minimize the total cost of the traffic on the overall transportation network while the demand is delivered on time. In [13] they present several meta-heuristics, the two main ones using a clustering and a multi-depot approach, respectively; in [14] they present a family of Multi-Start heuristics; and in [15] they propose a meta-heuristic based on GRASP (*Greedy Randomized Adaptive Search Procedure*) combined with Path Relinking to address the problem.

Separately, Crainic et al. [16] focus on the integrated short-term scheduling of operations and management of resources, for the general case involving a two-tier distribution structure, this being a City Logistics planning issue. Fundamentally a modeling paper, they aim to present a comprehensive view of the problem, identify issues and challenges, and propose and analyze modeling approaches, also identifying promising solution avenues, but without detailed algorithmic developments. [16] explores the reality of freight distribution in an urban context in further depth than other papers on the 2E-VRP. The goal of their formulation is to minimize the number of vehicles in the city while satisfying demand requirements.

In [17], Perboli et al. present valid inequalities based on the *Traveling Salesman Problem* (TSP) and the *Capacitated Vehicle Routing Problem* (CVRP), the network flow formulation, and the connectivity of the transport system graph. Subsequently, Perboli et al. [18] publish another paper with a twofold aim: first, to introduce the family of 2E-VRPs; and second, to consider in detail the basic version of the problem, the 2E-CVRP. Furthermore, they present a mathematical model for the 2E-CVRP, some valid inequalities, and two math-heuristics based on said model.

Hemmelmayr et al. [7] propose an adaptive large neighborhood search heuristic for the 2E-VRP and the *Location Routing Problem* (LRP). They consider the LRP to be a special case of the 2E-VRP in which vehicle routing is performed only at the second level. Additionally, they identify city logistics as a potential application of the 2E-VRP. They assert that in most cities, space is limited, especially in the city center, and has to be shared between passenger transport, both public and private, as well as parking facilities, and, furthermore, freight transportation produces congestion, polluting emissions and noise, and the presence of large, heavy vehicles is a discomforting factor for citizens. Moreover, they point out that large vehicles frequently have low average loads. They suggest that the key idea is to develop an integrated logistics system encompassing all components by consolidating freight that comes from different shippers and coordinating the freight transportation in the city.

Jepsen et al. [19] present an exact method for solving the symmetric 2E-CVRP. The method presented is based on an edge flow formulation of the CVRP introduced by Laporte et al. [21] and the *Split-Delivery CVRP* (SDCVRP) formulation proposed by Belenguer et al. [22]. The mathematical model is a relaxation for the 2E-CVRP and provides a lower bound for the problem but does not necessarily provide feasible solutions. A specialized branching scheme is employed to obtain feasible solutions, solving the problem to optimality. The objective is to minimize the sum of the vehicle travel costs and the handling costs at the satellites.

Baldacci et al. [20] describe a new mathematical formulation of the 2E-CVRP used to derive valid lower bounds and an exact method that decomposes the problem into a limited set of multi-depot CVRPs with side constraints.

Table 1 compares the above-mentioned papers studied by Cuda et al. [6] as the foremost relating to the 2E-VRP to one another and to this paper according to the following characteristics: if the formulation is multi-depot, multi-provider, if the fleet of vehicles at the same level considered is homogeneous or heterogeneous, if time windows are considered, and the objective to be minimized.

One can see in Table 1, as Cuda et al. also point out, that only Crainic et al. [16] consider the 2E-VRP with additional characteristics, these being a multi-depot, multi-provider formulation with heterogeneous fleets of vehicles at each level and time windows. However, the authors of [16] provide only a formulation of the problem and some solution methods, but no algorithm is presented, and to the best of the authors' knowledge, such algorithm has not yet been implemented and no computational experiments have been reported. Their formulation is also not multi-objective. The authors in this paper therefore identify the multi-objective 2E-VRP with multiple depots and providers, as well as other characteristics appropriate for the context of City Logistics and Urban Goods Movement, as yet unsolved.

The ultimate goal of the authors and the motivation of this research is to aid city governments in the development and implementation of a multi-echelon freight distribution software based on the 2E-VRP within a UGM context, and for this to be seriously considered, a formulation that goes beyond the simple single-depot single-provider model must be developed. The authors consider this model to be multi-objective as there are multiple stakeholders with potentially conflicting objectives. The main contribution of this paper therefore is a first-time multi-objective formulation of the multi-provider (or multi-commodity) heterogeneous vehicle 2E-VRP, from the perspective of a city government, this being a first step towards a manageable algorithm.

3. Problem Formulation

In this section the proposal for formulating and mathematically modeling the Multi-Objective Multi-Commodity 2E-VRP (tentatively identified as M^2-2E-VRP) with heterogeneous fleets is presented. This formulation considers the following stakeholders:

- providers;
- independent contractors for distribution or city companies (clients);
- city government and residents (taken together as their objectives may be considered to be the same).

Given these stakeholders, the four objective functions to be optimized in this formulation are the following:

- $f_1(s)$ transportation cost in the first echelon, relating to the costs of providers (see Equation (14));
- $f_2(s)$ transportation cost in the second echelon, of concern to independent contractors or clients, depending on who bears the brunt of the distribution costs in this level (see Equation (15));
- $f_3(s)$ number of vehicles used, relating to traffic contribution, of concern to the city government and residents (see Equation (16)); and
- $f_4(s)$ carbon emissions, of concern to the city government and residents (see Equation (17)).

3.1. Problem Representation

The proposed formulation of the M^2-2E-VRP assumes as known the sets of depots, satellites, customers and vehicles separated into their respective echelons. These sets are represented in this paper as follows:

- a set D of n_D depots;

TABLE 1. SUMMARY OF RELATED WORKS

Reference	Multi-depot	Multi-provider	Fleet	Time Windows	Objective (Minimize)
[13]	No	No	Homogeneous	No	Cost of traffic on network
[14]					
[15]					
[7]					Cost of shipping and handling
[17]					
[18]					
[19]					
[20]					
[16]	Yes	Yes	Heterogeneous	Yes	Number of vehicles
This paper				No	*Multiple (Transportation cost, vehicle usage, emissions)*

- a set S of n_S satellites;
- a set C of n_C customers;
- a set $L1$ of m_1 first-echelon vehicles; and
- a set $L2$ of m_2 second-echelon vehicles.

In the current version of the problem formulation, each depot i is associated with a unique product p; consequently, there are n_D products. Regarding the depots, satellites, and customers, the following data is required as well:

$$d_{ij} : \text{distance from } i \text{ to } j \text{ (length of arc)}$$

i and j may be any depot, satellite, or customer where an edge, or arc, exists. For practicality and considering the parameters used further ahead, the unit of measurement of distance will be assumed to be kilometers.

As this formulation considers heterogeneous fleets with differing characteristics in each vehicle, parameters referring to the capacity and carbon emissions of the vehicles do not describe whole sets of vehicles but are associated with individual vehicles. In this paper, k is used for *capacity*, c for *cost per kilometer* and g (garbage) for *carbon emissions*. *Cost per kilometer* is a single parameter for each vehicle that summarizes the inherent costs of operation, such as fuel consumption and maintenance. These parameters are represented as follows:

$$\begin{aligned}
k_q^1 &: \text{capacity of L1 vehicle } q \\
k_{q'}^2 &: \text{capacity of L2 vehicle } q' \\
c_q^1 &: \text{cost per kilometer of L1 vehicle } q \\
c_{q'}^2 &: \text{cost per kilometer of L2 vehicle } q' \\
g_q^1 &: \text{g CO}_2\text{/km emissions of L1 vehicle } q \\
g_{q'}^2 &: \text{g CO}_2\text{/km emissions of L2 vehicle } q'
\end{aligned}$$

In the classic VRP and subsequent formulations, a non-negative weight or demand may be attached to each city, or customer in our context, which must be satisfied [2]. This demand is usually one-dimensional for each customer, or one-commodity as it is known retronymically [23]. In this formulation however, multiple products are considered, known as multi-commodity, and the representation of the demand must reflect this multidimensionality. Therefore, this formulation considers a variable *demand* (represented by r as in *requires*) associated with both a customer and a specific product, resulting in practice in an array of demands by each customer:

$$r_i^p : \text{demand of product } p \text{ by customer } i$$

3.2. Solution Representation

The resulting solutions are sets of routes taken by the vehicles and the combination of freight carried and delivered by each vehicle to each point on its associated route. This information may be constructed with the following data:

- the usage of edge (i, j) by a vehicle q in each echelon (x_{ij}^q for L1 and y_{ij}^q for L2); and
- the volume of product p carried by vehicle q on each edge (i, j) it travels (z_{ij}^{pq}).

The aforementioned variables are defined as follows:

$$x_{ij}^q = \begin{cases} 1 & \text{if L1 vehicle } q \text{ travels } ij \text{ where } i, j \in D \cup S \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ij}^{q'} = \begin{cases} 1 & \text{if L2 vehicle } q' \text{ travels } ij \text{ where } i, j \in S \cup C \\ 0 & \text{otherwise} \end{cases}$$

$$z_{ij}^{pq} : \text{quantity of product } p \text{ in vehicle } q \text{ when traveling edge } (i, j).$$

Moreover, a vehicle usage variable is derived from x and y:

$$u_q^1 = \begin{cases} 1 & \text{if L1 vehicle } q \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

$$u_{q'}^2 = \begin{cases} 1 & \text{if L2 vehicle } q' \text{ is used} \\ 0 & \text{otherwise} \end{cases}$$

3.3. Constraints

In order for a solution to be valid, it must satisfy all customers' demands while complying with vehicle movement and capacity restrictions. A valid solution is restricted by the following constraints.

Constraint (1) ensures that the total quantity of a certain product carried to any customer must either satisfy or exceed (because it could also be intended for a subsequent customer) the stated demand.

$$\sum_{i \in S \cup C} \sum_{q \in L2} z_{ij}^{pq} \geq r_j^p \qquad \forall j \in C, \forall p \in \{1 \ldots n_D\} \tag{1}$$

Constraints (2) and (3) ensure that the quantity of freight loaded onto an L1 vehicle at a depot, or L2 vehicle at a satellite, respectively, does not exceed the vehicle capacity.

$$\sum_{p}^{n_D} z_{ij}^{pq} \leq k_q^1 \quad \forall q \in L1, \forall i \in D, \forall j \in S \tag{2}$$

$$\sum_{p}^{n_D} z_{ij}^{pq'} \leq k_{q'}^2 \quad \forall q' \in L2, \forall i \in S, \forall j \in C \tag{3}$$

Constraints (4) and (5) ensure that each L1 vehicle begins and ends its trip at only one depot, and that each L2 vehicle begins and ends its trip at only one satellite.

$$\sum_{i \in D} \sum_{j \in S} x_{ij}^q = \sum_{i \in S} \sum_{j \in D} x_{ij}^q \leq 1 \quad \forall q \in L1 \tag{4}$$

$$\sum_{i \in S} \sum_{j \in C} y_{ij}^{q'} = \sum_{i \in C} \sum_{j \in S} y_{ij}^{q'} \leq 1 \quad \forall q' \in L2 \tag{5}$$

Constraints (6) and (7) ensure that the depot or satellite from which a vehicle departs is also the same to which it returns.

$$\sum_{j \in S} x_{ij}^q = \sum_{j \in S} x_{ji}^q \leq 1 \quad \forall q \in L1, \forall i \in D \tag{6}$$

$$\sum_{j \in C} y_{ij}^{q'} = \sum_{j \in C} y_{ji}^{q'} \leq 1 \quad \forall q' \in L2, \forall i \in S \tag{7}$$

Constraints (8) and (9) ensure that trips are contiguous and no vehicle visits the same location more than once.

$$\sum_{i \in D \cup S} x_{ij}^q = \sum_{k \in D \cup S} x_{jk}^q \leq 1 \quad \forall q \in L1, \forall j \in D \cup S \tag{8}$$

$$\sum_{i \in S \cup C} y_{ij}^{q'} = \sum_{k \in S \cup C} y_{jk}^{q'} \leq 1 \quad \forall q' \in L2, \forall j \in S \cup C \tag{9}$$

The definitions of x and y already prevent L1 vehicles from traveling to customers and L2 vehicles from traveling to depots, (10) and (11) additionally prevent L1 vehicles from traveling between depots and L2 vehicles from traveling between satellites, respectively.

$$\sum_{i \in D} \sum_{j \in D} \sum_{q \in L1} x_{ij}^q = 0 \tag{10}$$

$$\sum_{i \in S} \sum_{j \in S} \sum_{q' \in L2} y_{ij}^{q'} = 0 \tag{11}$$

Finally, (12) and (13) ensure the consistency of z, that products are only carried by a vehicle q on arcs said vehicle effectively travels.

$$z_{ij}^{pq} = x_{ij}^q z_{ij}^{pq} \quad \forall p \in \{1 \ldots n_D\}, \forall q \in L1, \forall i, j \in D \cup S \tag{12}$$

$$z_{ij}^{pq'} = y_{ij}^{q'} z_{ij}^{pq'} \quad \forall p \in \{1 \ldots n_D\}, \forall q' \in L2, \forall i, j \in S \cup C \tag{13}$$

3.4. Objective Functions

Although in general some objective functions can be minimized while maximizing other objective functions, in this work each of the considered objective functions is formulated in a single optimization context (i.e. only minimization). In this work, optimizing the following four objective functions is proposed in order to obtain optimal solutions:

- first echelon transportation cost minimization;
- second echelon transportation cost minimization;
- vehicle quantity minimization; and
- carbon emissions minimization.

3.4.1. Transportation Cost Minimization. Typically, as seen in Table 1, most works dealing with 2E-VRP consider some form of traffic or transportation or shipping cost minimization as the only objective to optimize. This is included in this paper as transportation cost. However, it is divided into two separate objective functions, one for the first echelon and one for the second, given that they may affect different stakeholders as previously mentioned (providers and contractors or clients). This takes into account that two different solutions may have the same or similar cost of transportation, but one with more routing (and therefore cost) in the first echelon, and the other in the second. Furthermore, although previous works [10] use only a single cost parameter for each arc to calculate the transportation cost, in this work two are used (i.e. c and d). This is due to previous works' use of homogeneous fleets, where the cost of operation of all vehicles would be the same and therefore the total cost would be directly proportional to the total accumulated distance covered by all vehicles. For this reason, there was no need to consider cost of operation separately from distance. However, in this present work, the fleets are heterogeneous and the cost of operation will in all likelihood differ between vehicles (e.g. fuel consumption of a diesel vehicle compared to a petrol vehicle of same or similar capacity).

The objective functions regarding transportation cost are mathematically formulated below.

Minimize the transportation cost in the first echelon:

$$f_1(s) = \sum_{q \in L1} \sum_{i \in D \cup S} \sum_{j \in D \cup S} d_{ij} x_{ij}^q c_q^1 \tag{14}$$

Minimize the transportation cost in the second echelon:

$$f_2(s) = \sum_{q' \in L2} \sum_{i \in S \cup C} \sum_{j \in S \cup C} d_{ij} y_{ij}^{q'} c_{q'}^2 \tag{15}$$

where:

s :	evaluated solution of the problem;
$f_1(s)$:	total first echelon transportation cost;
$f_2(s)$:	total second echelon transportation cost;
$L1$:	set of first-echelon vehicles;
$L2$:	set of second-echelon vehicles;

$D:$ set of depots;
$S:$ set of satellites;
$C:$ set of customers;
$d_{ij}:$ distance from i to j;
$x_{ij}^{q} \in \{0,1\}:$ indicates if L1 vehicle q travels (1) from i to j or not (0);
$y_{ij}^{q'} \in \{0,1\}:$ indicates if L2 vehicle q' travels (1) from i to j or not (0);
$c_q^1:$ cost per kilometer of L1 vehicle q;
$c_{q'}^2:$ cost per kilometer of L2 vehicle q'.

3.4.2. Vehicle Quantity Minimization. A situation may arise in which the solution with the lowest transportation cost utilizes all available vehicles. However, it may be desirable to keep the vehicles traveling at a low number in order to avoid saturating the transportation network. Therefore, minimizing the quantity of vehicles used is considered as an objective function, formulated as follows:

$$f_3(s) = \sum_{q \in L1} u_q^1 + \sum_{q' \in L2} u_{q'}^2 \tag{16}$$

where:

$s:$ evaluated solution of the problem;
$f_3(s):$ total number of vehicles used;
$L1:$ set of first-echelon vehicles;
$u_q^1 \in \{1,0\}:$ indicates if L1 vehicle q is used (1) or not (0);
$L2:$ set of second-echelon vehicles;
$u_{q'}^2 \in \{1,0\}:$ indicates if L2 vehicle q' is used (1) or not (0).

3.4.3. Carbon Emissions Minimization. Few papers concerning 2E-VRP, if any, and none to the knowledge of the authors, explicitly consider environmental impact minimization as an objective function to be optimized. Environmental impact is however a more studied subject within the framework of City Logistics and Urban Goods Movement, specifically within the field of city logistics sustainability [24]. Urban mobility accounts for 40% of all CO_2 emissions of road transport and up to 70% of other pollutants from transport, and traffic emissions in general are responsible for 70% of cancerous and other dangerous substances [25]. As this paper concerns 2E-VRP from a UGM perspective within a City Logistics framework, the authors consider environmental impact minimization as a necessary goal. This objective function is formulated as follows:

$$f_4(s) = \sum_{q \in L1} \sum_{i \in D \cup S} \sum_{j \in D \cup S} d_{ij} x_{ij}^{q} g_q^1 \quad + \sum_{q' \in L2} \sum_{i \in S \cup C} \sum_{j \in S \cup C} d_{ij} y_{ij}^{q'} g_{q'}^2 \tag{17}$$

where:

$s:$ evaluated solution of the problem;
$f_4(s):$ total CO_2 emissions;
$L1:$ set of first-echelon vehicles;
$D:$ set of depots;
$S:$ set of satellites;
$d_{ij}:$ distance from i to j;
$x_{ij}^{q} \in \{0,1\}:$ indicates if L1 vehicle q travels (1) from i to j or not (0);
$g_q^1:$ g CO_2/km emissions of L1 vehicle q;
$L2:$ set of second-echelon vehicles;
$C:$ set of customers;
$y_{ij}^{q'} \in \{0,1\}:$ indicates if L2 vehicle q' travels (1) from i to j or not (0);
$g_{q'}^2:$ g CO_2/km emissions of L2 vehicle q'.

Objective function (17) potentially conflicts with the first two relating to transportation cost, as vehicles with a lower rate of emissions (e.g. electric or hybrid) may currently have higher operation costs, depending on how these are calculated, due to the higher cost of acquisition, maintenance, and fuel, or limited supply thereof [26].

It should be noted that other pollutants, such as carbon monoxide or nitrogen oxides, can also be considered and appended as additional objective functions within this novel formulation. It is only a matter of adding the required information to the vehicles and formulating the objective function based on (17).

4. Motivational Examples

To better illustrate the approach presented in this paper and its practicality for reducing traffic congestion within the city and other problems, such as pollution, a pair of simple examples is provided. The examples differ in several characteristics, most notably the location of the CDCs or satellites, these being outside the area of clients in the first example, emulating a clear restricted area, and within the area in the second example.

For sake of simplicity, in both examples, the geographic distribution (of customers, providers and satellites) follows a regular and uniform pattern. The distances resemble those in Asuncion, assuming the providers' depots are located in the Greater Asuncion Area (e.g. Luque, Villa Elisa) and the customers are within Asuncion's commercial districts. Each provider supplies a different product and all customers require both products in equal quantities. Both examples have two providers and both providers have one vehicle each, an Isuzu NPR with the following characteristics: (1) Payload or capacity: 3500 kg, (2) Fuel consumption: diesel, 0.196 l/km, and (3) CO_2 emissions: 500 g/km. The smaller, greener second-echelon vehicle used in these examples is the Renault Kangoo with the following characteristics: (1) Payload: 800 kg, (2) Fuel consumption: petrol, 0.097 l/km,

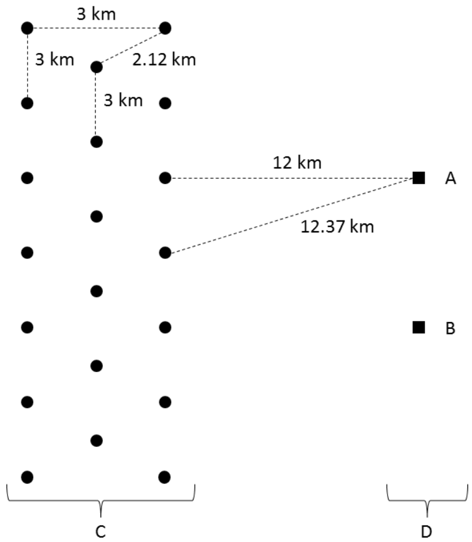

Figure 1. Layout with 2 providers and 20 customers

and (3) CO_2 emissions: 180 g/km. These characteristics are approximate, yet serve to paint a realistic scenario.

To exemplify the calculation of the objective functions described in this paper, the measurements of these functions are presented for the two-echelon distributions at the end of both examples. Note that to calculate the costs, the current fuel prices in Paraguay (in Guaranies or Gs.[1]) were considered: Gs. 4290 for a litre of standard diesel and an average Gs. 5690 for a litre of petrol, and for the calculation of f_1 and f_2, the c parameter of the vehicles used considered only the cost of fuel consumption.

4.1. Example 1

Consider a scenario with 20 customers (set C) and 2 providers (set D), as seen in Figure 1.

As both providers A and B have one vehicle with a payload of 3500 kg, a demand by the customers of 175 kg of each product provided is assumed, in order to force both vehicles to full capacity and to visit each customer in a conventional setup where the delivery is directly from the depots to the customers. This is favorable for providers as their scheduling is not always efficient enough to have all trucks leave the depot at full capacity. A simple and relatively intelligent routing could look like Figure 2.

Next, CDCs or satellites are introduced. Specifically, six satellites (set S) are inserted following a uniform pattern, practically another column to the grid of customers, as seen in Figure 3.

In the current setup, the providers' trucks will only travel to the CDCs to drop off their goods, where they will be consolidated onto the smaller vehicles, the previously mentioned Kangoo, that deliver the goods to the customers. The Kangoo's payload of 800 kg allows it to satisfy the

1. 1 USD $\approx$ 5500 Gs. in 2017.

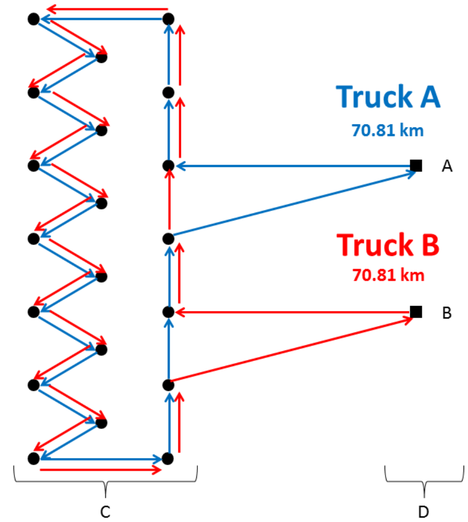

Figure 2. Conventional distribution in Example 1

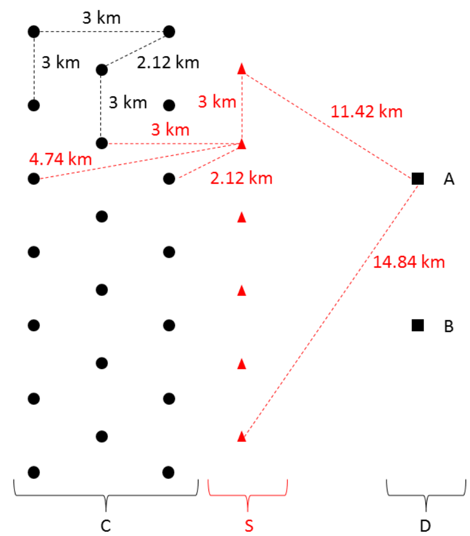

Figure 3. Layout with 2 providers, 6 satellites and 20 customers

demands for both products A and B for two customers. A relatively intelligent routing could thus look like Figure 4. This distribution results in a greater total distance covered compared to the conventional distribution. However, the second-echelon (L2) routing or routing between customers, i.e. excluding the trips to and from the depots and between the satellites, and including the trips from satellites to customers and back, and between customers, covers slightly less than in the conventional distribution. This means the traffic within the city's hypothetical commercial district is reduced. The total cost is nearly identical.

The results of both strategies can be compared side by side in Table 2.

The greatest change is a more than 18% reduction of total CO_2 emissions, showcasing the environmental friend-

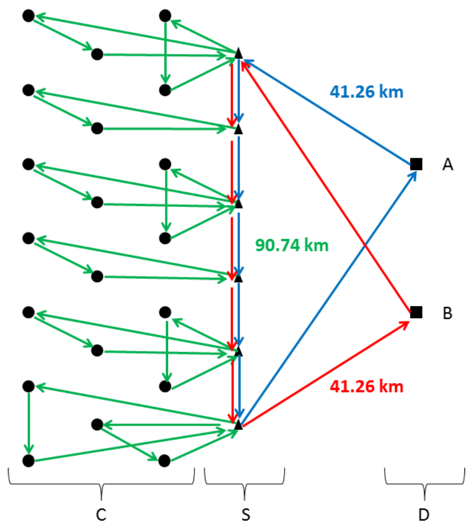

Figure 4. Two-echelon distribution in Example 1

TABLE 2. CONVENTIONAL AND TWO-ECHELON DISTRIBUTIONS IN EXAMPLE 1 COMPARED

Measurements	Conventional	2-Echelon	Change
Distance traveled (km)	141.62	173.26	22.44%
L2 routing (km)	92.88	90.74	-2.3%
Total cost (Gs.)	118960	119405	0.37%
Total CO_2 emissions (g)	70810	57593	-18.67%

liness of the proposed approach. Albeit an increase in total travel, the second-echelon routing is reduced by 2.3%, and the cost is nearly identical, with only a small, negligible increase. Additionally to the reduced second-echelon routing and carbon emissions, and the similar cost, the multi-level distribution scenario implies for the customer only one visit by an urban-friendly vehicle that delivers its whole demand, instead of two visits by larger, slower trucks, that likely occupy more space when parking and take more time to unload. Furthermore, the time to deliver may potentially be reduced as well, as the first-echelon trucks need only serve the satellites, while second-echelon vehicles may already simultaneously deliver the goods to the customers, given that all required goods have already been consolidated onto the second-echelon vehicles in question. The total cost and emissions could be further reduced if hybrid or electric vehicles are considered for the second echelon [27].

The measurements of the objective functions in this example are summarized as follows:

$f_1(s)$ **First echelon cost** Gs. 69386.1168
$f_2(s)$ **Second echelon cost** Gs. 50082.1282
$f_3(s)$ **Vehicle quantity** 12 vehicles
$f_4(s)$ **Carbon emissions** 57593.2 g CO_2

4.2. Example 2

Consider a scenario with 16 customers (set C) and 2 providers (set D), as seen in Figure 5.

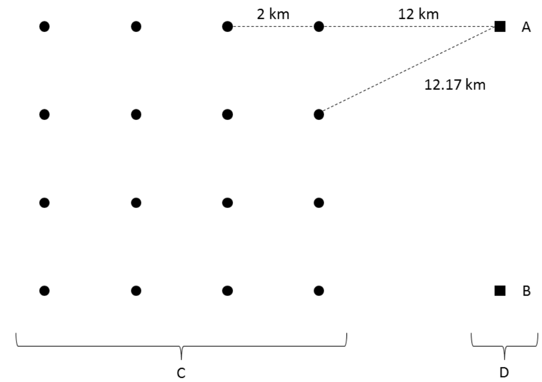

Figure 5. Layout with 2 providers and 16 customers

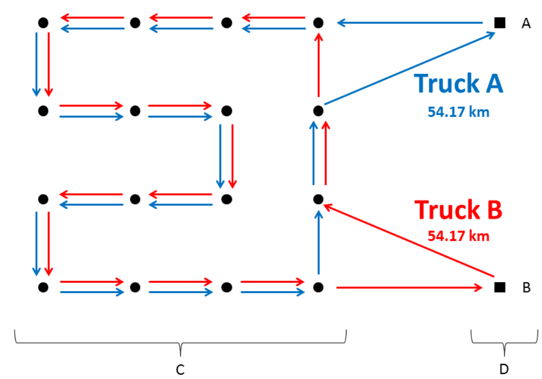

Figure 6. Conventional distribution in Example 2

A demand by the customers of 200 kg of each product provided is assumed, resulting in a total demand of 3200 kg for each product, meaning the providers' trucks will each be loaded to 91.4% capacity and then visit each customer once. A simple and relatively intelligent routing could look like Figure 6.

Next, CDCs or satellites are introduced. Specifically, four satellites (set S) are inserted following a uniform pattern, practically forming a smaller grid within the grid of customers, as seen in Figure 7.

In the current setup, the providers' trucks will only travel to the CDCs to drop off their goods, where they will be consolidated onto the smaller vehicles, the Kangoo, that deliver the goods to the customers. The Kangoo's payload of 800 kg allows it to satisfy the demands for both products A and B for two customers. A relatively intelligent routing could thus look like Figure 8. Just as in Example 1, this distribution results in a greater total distance covered compared to the conventional distribution and less second-echelon (L2) routing or routing between customers, including the routing between satellites by the trucks as in this example the satellites are located among the customers. This means the traffic within the hypothetical commercial district is reduced.

The results of both strategies can be compared side by

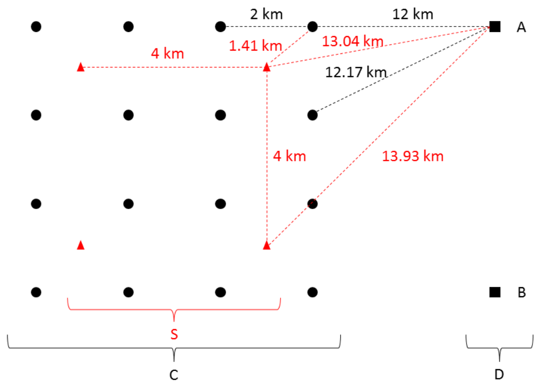

Figure 7. Layout with 2 providers, 4 satellites and 16 customers

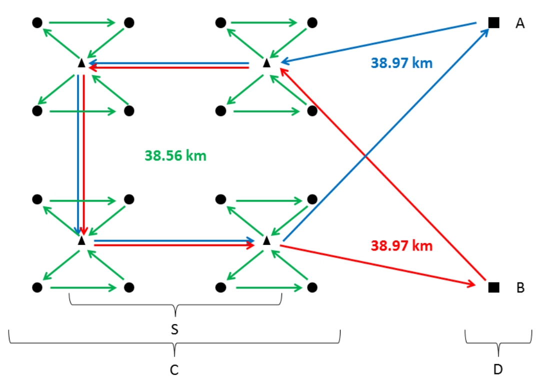

Figure 8. Two-echelon distribution in Example 2

side in Table 3.

The reduction in CO_2 emissions is still the most notable, albeit at 15% slightly less than in the first example. Unlike the first example, the overall cost is reduced by nearly 5%. The total distance covered is augmented considerably less and the second-echelon routing is reduced more than in Example 1, even though in this example the routing by trucks between satellites was considered as well.

In the same manner as in the previous example, the multi-level distribution scenario implies for the customer only one visit by an urban-friendly vehicle instead of two visits by trucks; the time to deliver may potentially be reduced as well, as the first-echelon trucks need only serve the satellites, while second-echelon vehicles may already simultaneously deliver the goods to the customers; and the total cost and emissions could be further reduced if hybrid or electric vehicles are considered for the second echelon.

The measurements of the objective functions in this example are summarized as follows:

$f_1(s)$ **First echelon cost** Gs. 65469.6
$f_2(s)$ **Second echelon cost** Gs. 21285.12
$f_3(s)$ **Vehicle quantity** 10 vehicles
$f_4(s)$ **Carbon emissions** 45910.8 g CO_2

TABLE 3. CONVENTIONAL AND TWO-ECHELON DISTRIBUTIONS IN EXAMPLE 2 COMPARED

Measurements	Conventional	2-Echelon	Change
Distance traveled (km)	108.34	116.5	7.53%
L2 routing (km)	60	50.56	-8.71%
Total cost (Gs.)	91006	86756	-4.67%
Total CO_2 emissions (g)	54170	45911	-15.25%

5. Conclusions and Future Work

This work presented the case for using a multi-objective multi-level distribution strategy concerning all significant stakeholders, both businesses and city authorities, as means to reduce traffic congestion and its resulting pollution in an urban context while minimizing financial loss.

The proposed strategy is based on organizing the commercial traffic related to urban goods movement, from the viewpoint of a city government seeking a holistic solution method, within the framework of a two-tiered distribution scheme known as the *Two-Echelon Vehicle Routing Problem* (2E-VRP). Said strategy adapts the 2E-VRP to the context of City Logistics and Urban Goods Movement by considering multiple providers, products, depots, stakeholders and objectives, and heterogeneous vehicle fleets, thus receiving the name of *Multi-Objective Multi-Commodity Two-Echelon Vehicle Routing Problem* (M^2-2E-VRP).

Several stakeholders were considered, namely providers, independent contractors for distribution, clients, residents and the city government. Based on the objectives of these stakeholders, four objective functions were considered and formulated for multi-objective optimization: (i) first-echelon transportation cost minimization (objective of providers), (ii) second-echelon transportation cost minimization (objective of clients or independent contractors), (iii) vehicle quantity minimization (objective of city government and residents) and (iv) carbon emissions minimization (objective of city government and residents). Solutions to the aforementioned problem considering these objectives would provide routing schedules that simultaneously minimize traffic and its related costs as well as pollution due to CO_2 emissions. The model however is flexible and not limited or bound to these objectives, and can be easily modified to consider more or different objectives, such as minimizing other types of emissions, maximizing the usage of electric vehicles, or minimizing the number of satellites used.

In order to solve the formulated problem, a multi-objective algorithm must be developed. To the best of the knowledge of the authors, such an algorithm for the 2E-VRP has not yet been published and the authors propose to do so with a *Multi-Objective Evolutionary Algorithm* (MOEA) given that said algorithms generate sets of solutions allowing for a relatively straightforward approximation of the Pareto front in subsequent iterations.

The long-term goal of the present research is to develop and implement algorithms and software to aid city governments in holistically optimizing commercial traffic within their urban landscapes. This work provides a first formulation useful for the development of initial algorithms and may lead to broader, more complete and comprehensive mathematical models and formulations that eventually serve as foundations for the software required for the aforementioned endeavor to succeed.

The authors consider analyzing and formulating more objectives and data concerning the vehicles and products, such as additional vehicle emissions rates, constraints on which products can be loaded together considering their compatibility, or minimizing travel time as an additional objective, as steps towards evolving the present formulation towards a more realistic and integral one that better reflects the complexity of commercial urban traffic. Furthermore, in order to gain a deeper understanding of the optimization of multi-level distribution, algorithms that solve the M^2-2E-VRP as proposed in this work should be developed. Consequently, at the time of writing, the authors are developing a MOEA towards this goal.

As further future works, the authors are analyzing the applications of this research for the reduction of traffic congestion in cities of Ecuador within the framework of the DEMOSDUM project[2].

6. Acknowledgments

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References

[1] D. Cattaruzza, N. Absi, D. Feillet, and J. González-Feliu, "Vehicle routing problems for city logistics," *EURO Journal on Transportation and Logistics*, pp. 1–29, 2015.

[2] G. Laporte, "The vehicle routing problem: An overview of exact and approximate algorithms," *European journal of operational research*, vol. 59, no. 3, pp. 345–358, 1992.

[3] T. G. Crainic, N. Ricciardi, and G. Storchi, "Advanced freight transportation systems for congested urban areas," *Transportation Research Part C: Emerging Technologies*, vol. 12, no. 2, pp. 119–137, 2004.

[4] J. Gonzalez-Feliu, "Models and methods for the city logistics: The two-echelon capacitated vehicle routing problem," Ph.D. dissertation, Politecnico di Torino, March 2008.

[5] ——, "Vehicle routing in multi-echelon distribution systems with cross-docking: A systematic lexical-metanarrative analysis," *Computer and Information Science*, vol. 6, no. 3, p. 28, 2013.

[6] R. Cuda, G. Guastaroba, and M. G. Speranza, "A survey on two-echelon routing problems," *Computers & Operations Research*, vol. 55, pp. 185–199, 2015.

[7] V. C. Hemmelmayr, J.-F. Cordeau, and T. G. Crainic, "An adaptive large neighborhood search heuristic for two-echelon vehicle routing problems arising in city logistics," *Computers & operations research*, vol. 39, no. 12, pp. 3215–3228, 2012.

[8] H. Hernández-Pérez and J.-J. Salazar-González, "The Multi-commodity Pickup-and-Delivery Traveling Salesman Problem," *Networks*, vol. 63, no. 1, pp. 46–59, 2014.

2. https://www.researchgate.net/project/Math-AmSud-DEMOSDUM-Design-and-Model-of-an-Optimal-System-for-Urban-Freight-Distribution-for-critical-and-heterogeneous-Km2-in-Guayaquil-and-Quito-cities-in-Ecuador

[9] C. A. Coello Coello, G. B. Lamont, and D. A. Van Veldhuizen, "Evolutionary algorithms for solving multi-objective problems," 2007.

[10] J. Gonzalez-Feliu, G. Perboli, R. Tadei, and D. Vigo, "The two-echelon capacitated vehicle routing problem," 2008.

[11] J. Gonzalez-Feliu, "Two-echelon freight transport optimisation: unifying concepts via a systematic review," *Working Papers on Operations Management*, vol. 2, no. 1, p. 18, 2011.

[12] ——, "Cost optimisation in freight distribution with cross-docking: N-echelon location routing problem," *PROMET-Traffic&Transportation*, vol. 24, no. 2, pp. 143–149, 2012.

[13] T. G. Crainic, S. Mancini, G. Perboli, and R. Tadei, "Clustering-based heuristics for the two-echelon vehicle routing problem," *Montreal, Canada, Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation*, vol. 17, p. 26, 2008.

[14] ——, "Multi-start heuristics for the two-echelon vehicle routing problem," in *European Conference on Evolutionary Computation in Combinatorial Optimization*. Springer, 2011, pp. 179–190.

[15] ——, "Grasp with path relinking for the two-echelon vehicle routing problem," in *Advances in Metaheuristics*. Springer, 2013, pp. 113–125.

[16] T. G. Crainic, N. Ricciardi, and G. Storchi, "Models for evaluating and planning city logistics systems," *Transportation science*, vol. 43, no. 4, pp. 432–454, 2009.

[17] G. Perboli and R. Tadei, "New families of valid inequalities for the two-echelon vehicle routing problem," *Electronic notes in discrete mathematics*, vol. 36, pp. 639–646, 2010.

[18] G. Perboli, R. Tadei, and D. Vigo, "The two-echelon capacitated vehicle routing problem: models and math-based heuristics," *Transportation Science*, vol. 45, no. 3, pp. 364–380, 2011.

[19] M. Jepsen, S. Spoorendonk, and S. Ropke, "A branch-and-cut algorithm for the symmetric two-echelon capacitated vehicle routing problem," *Transportation Science*, vol. 47, no. 1, pp. 23–37, 2013.

[20] R. Baldacci, A. Mingozzi, R. Roberti, and R. W. Calvo, "An exact algorithm for the two-echelon capacitated vehicle routing problem," *Operations Research*, vol. 61, no. 2, pp. 298–314, 2013.

[21] G. Laporte and Y. Nobert, "A branch and bound algorithm for the capacitated vehicle routing problem," *Operations-Research-Spektrum*, vol. 5, no. 2, pp. 77–85, 1983.

[22] J. Belenguer, M. Martinez, and E. Mota, "A lower bound for the split delivery vehicle routing problem," *Operations Research*, vol. 48, no. 5, pp. 801–810, 2000.

[23] H. Hernández-Pérez and J.-J. Salazar-González, "Heuristics for the one-commodity pickup-and-delivery traveling salesman problem," *Transportation Science*, vol. 38, no. 2, pp. 245–255, 2004.

[24] F. Russo and A. Comi, "City characteristics and urban goods movements: A way to environmental transportation system in a sustainable city," *Procedia-Social and Behavioral Sciences*, vol. 39, pp. 61–73, 2012.

[25] A. B. Silva and A. Ribeiro, "An integrated planning for cities to promote sustainable mobility," in *Proceedings of European Transport Conference*. Citeseer, 2009.

[26] O. Van Vliet, A. S. Brouwer, T. Kuramochi, M. van Den Broek, and A. Faaij, "Energy use, cost and co 2 emissions of electric cars," *Journal of power sources*, vol. 196, no. 4, pp. 2298–2310, 2011.

[27] K. Parks, P. Denholm, and A. J. Markel, "Costs and emissions associated with plug-in hybrid electric vehicle charging in the xcel energy colorado service territory," 2007.