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A Mathematical Programming for a Special Case of 2E-LRP in Cash-In-Transit Sector Having Rich Variants

Alireza Fallah-Tafti & Mohammad-Ali Vahdatzad*

Alireza Fallah-Tafti, *PhD candidate, department of Industrial Engineering, Yazd University, Yazd, Iran*
Mohammad-Ali Vahdatzad, *Assistant Professor, department of Industrial Engineering, Yazd University, Yazd, Iran*

KEYWORDS

Two-echelon location-routing problem;
Mixed integer linear programming;
Cash in transit;
Multiple objective optimization;
Augmented ε-constraint method

ABSTRACT

This article proposes a special case of a two-echelon location-routing problem (2E-LRP) in the cash-in-transit (CIT) sector. To tackle this realistic problem and make the model applicable, a rich LRP is presented considering several existing real-life variants and characteristics named BO-2E-PCLRPSD-TW, including different objective functions, multiple echelons, multiple periods, capacitated vehicles, distribution centers and automated teller machines (ATMs), different types of vehicles in each echelon, and single-depot with different time windows. Since routing plans in the CIT sector ought to be safe and efficient, the minimization of total transportation risk and cost are considered simultaneously as objective functions. Then, such a complex problem is formulated in mathematical mixed integer linear programming (MMILP). To validate the presented model and the formulation and to solve the problem, the latest version of ε-constraint method namely AUGMECON2 is applied. This method is specially efficient for solving multi-objective integer programing (MOIP) problems and provides the exact Pareto fronts. Results substantiate the suitability of the model and the formulation.
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1. Introduction

The two-echelon location-routing problem (2E-LRP) is a particular case of multi-echelon systems where the network is composed of two echelons. In such problems, typically, freight is delivered to the destinations moving mandatory through intermediate facilities and after taking place of operations such as storage or integration. The 2E-LRP involves both strategic planning decisions (e.g., number and location of facilities) and tactical planning decisions (e.g., customer allocation to the intermediate facilities and routing). Thus, a proper location of facilities as well as optimum allocation of customers to these facilities alongside suitable routing can considerably reduce the traffic congestion, decrease cost, and increase security of transportation[1].

Among all types of commodities, banknotes and coins are crucial in our daily lives. Physical currency, despite the sharp usage of electronic payment mechanism, is still the most widely used payment mechanism and is expected to preserve its supremacy in the near future [2]. Besides, transportation of this type of

* **Corresponding author:** ***Mohammad-Ali Vahdatzad***
Email: *mvahdat@yazd.ac.ir*
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commodities is exposed always to high risk such as robbery. Hence, currency distribution is of great challenges for Banks' managers and CIT (cash-in-transit) companies to satisfy the needed amount of cash for bank branches and/or automated teller machines (ATMs) with the minimum traveled cost and risk.

Many papers have considered the location-routing problem (LRP) in different echelons; however, the number of researches that considered the issue of risk in the LRP is few. However, a real-world problem such as cash distribution usually includes many constraints and assumptions requiring a complete mathematical modelling. Moreover, in real-life LRPs, usually decision-makers (DMs) have to cope with different objectives concurrently. Hence, the main aim of this paper is to propose a special case of 2E-LRP in a CIT sector with multiple periods, multiple capacitate vehicles with time windows, and different objective functions in order to make it applicable to real-life problems. Then, to solve such a rich and complex problem, at first, a mathematical mixed integer linear programming (MMILP) formulation is proposed; then, the latest improved version of ε-constraint that is very efficient to solve multiple objective integer programming (MOIP) problems is applied.

The rest of the paper is organized as follows: a comprehensive literature review is given in Section 2. Section 3 describes the problem and elaborates the mathematical formulation. In Section 4, a multi-objective optimization method is presented. Section 5 reports the computational results. Finally, Section 6 presents the conclusion and future research.

2. Literature Review

This section reviews the related literature on the location-routing problems, specifically those having studied LRP modelling extensions such as multiple echelons, multiple periods and time windows, cash-in-transit (CIT) sector and its associated transportation risk, and MOIP solution approaches.

The location-routing problems (LRP) represent a special case of vehicle routing problem (VRP), where both strategic decision (e.g., optimal number and location of depots) and tactical one (e.g., commodity flow and vehicle type) are determined simultaneously preventing sub-optimality caused by the separated consideration [3]. Watson-Gandy and Dohrn [4] clearly studied this problem for the first time in 1973 and, from that time onwards, it has been extending in various forms by both researchers and practitioners. There are numerous types of variants and characteristics in LRP. However, taking the lately published review articles into account [5, 6], researchers do try to consider as many variants and constraints as possible making the model more realistic and applicable. For instance, some researchers (e.g., [7], [8], [9] and [10]) studied capacitated LRP (CLRP) where vehicles and/or depots have a limited capacity of store goods. Another type of such a problem can be obtained by adding a multi-period horizon to the typical LRP called multi-period/periodic LRP (PLRP), in which either periodic delivery of time-sensitive shipments is related to each customer (e.g., [11] and [12]) or depots can be open/closed in a subset of time periods (e.g., [1]). A time-window constraint, which has gained more attention by researchers recently (e.g., [13], [14] and [15]), is another more complex real-life routing problem variant; in this respect, either delivery loaded on a vehicle should be made within an allowable time window or a vehicle should return to the depot/parking space within a pre-defined time window. Another very important characteristic in routing problem is multiple-echelon (NE-LRP) which has very newly attracted the interests of researchers. NE-LRP, judging from the number of publications of the last decade and the review paper proposed by Drexl and Schneider [16], is of the most important LRP modelling extensions.

Two-echelon LRP (2E-LRP) is a special case of NE-LRP in which the network is composed of two echelons and three stages including depot, intermediate facilities, and customers and, typically, available commodities at depots should be delivered to the customers moving compulsory through intermediate facilities. The first effort in 2E-LRP dates back to 80s by Jacobsen and Madsen [17]. After that, Madsen [18] and Laporte [19] studied the 2E-LRP in which the location decision in the intermediate facilities and routing in both echelons was made. The most studied member of the class of 2E-LRP is the 2E-capacitated LRP (2E-CLRP) [20] which has been recently found in few papers (e.g., [21], [22], [23] and [24]). Nguyen

[25, 26] proposed a special case of 2E-CLRP in which only a single depot with a pre-known location exists in the model (2E-CLRPSD). Simultaneous pickup and delivery is one other variant in routing problem (e.g.,[27]). Rahmani et al. [28] proposed a new extension of 2E-LRP, having multiple products with pickup and delivery (LRP-MPPD-2E) and, then, used a clustering-based approach to solving the problem. Vidovi et al. [29] developed a mathematical modelling for a 2E-LRP in the application of non-hazardous recyclables collection with profit and distance-dependent collection rates.

The research papers cited above mainly applied the LRP in distribution of goods such as food, document/parcel delivery and waste collection, corroborating the wide applicability of the LRP models in practice. However, the LRP can also be used in distribution of valuable goods such as banknotes and coins which are highly exposed to the risk of being robbed. Recently, the issue of "increased security", equivalent to "reduced risk", during the transportation of valuable products (i.e., cash) has increased significant attention in academic world to cope with the real-life problems. A peripatetic routing problem was proposed by Krarup [30] to improve the security of transportation so that customers can be visited for more than one time within a planning horizon; however, the same road segment cannot be used more than once. Calvo and Cordone [31] presented the "unpredictable" routes by generating numerous solutions through defining particular time windows with a minimum and maximum time lag between two consecutive visits of the same customer. Yan et al. [32] introduced a different unpredictability approach that incorporates a new concept of similarity for routing problems by taking both time and space measures into account. Talarico et al. [33] proposed an index of global route risk, namely the maximum exposure to risk, to model the problem of routing vehicles in the CIT sector by introducing a variant of the renowned capacitated VRP. They presented a risk index associated with a robbery proportional both to the amount of cash carried by vehicle and time/distance covered by the vehicle transporting the cash. Lately, Kahfi and Tavakkoli-Moghadam [34] proposed a route risk index between each of two consecutive nodes which is a number between 0 (no risk) and 1 (highest risk). To calculate this, they used the subjective opinion of experts considering the weighted criteria such as road type (high way, street, alley, etc.), allowed traffic type (one-way or two-way), street width, and street traffic. They formulated the model with few constraints and, then, applied it to a real-case problem.

Another important characteristic of real-life LRPs is that DMs, very often, have to simultaneously manage several objective functions and those are usually in conflict with each other. The above-mentioned studies deal with a single-objective function focused on economic aspects. However, the contribution of papers in the LRPs having considered multiple objectives is small and, to the best of our knowledge, there is no research paper in the area of 2E-LRP in CIT sector with more than one objective. Govindan et al. [35] and Ghezavati and Beigi [36] proposed a bi-objective in 2E-LRP. The former formulated a nonlinear mathematical model and, then, presented a hybrid metaheuristic optimization approach called MHPV to solve the problem, and the latter formulated a linear mathematical model and used non-dominated sorting genetic algorithm (NSGAII) as a metaheuristic solution approach. Connecting to the CIT routing problem with more than one objective function, Talarico et al. [37] and Kahfi and Tavakkoli-Moghaddam [34] presented bi-objective models in a single echelon and single period to minimize total travel cost and maximize secure vehicle routes. Talarico et al. [37] applied a novel metaheuristics technique named PMOO, including both multi-objective optimization and multi-criteria decision making into a single metaheuristic algorithm. Kahfi and Tavakkoli-Moghaddam [34] used two meta-heuristic approaches, including multi-objective bath algorithm (MOBA) and NSGAII, to solve the problem.

Considering the lately exhaustive literature review papers on LRP [11, 16], VRP [5, 6, 16, 38] and specifically 2E-LRP [20], the following points can be suggested as conclusions:

- Less than 9% of the related papers have considered at least three constraints (e.g., capacity of vehicles, heterogeneous fleet of vehicle, time windows, periodic VRP, pickup

and delivery, split delivery, etc.) in their routing problems simultaneously [6, 38], while some particular variants such as periodic VRP can hardly be seen.

- Small percentage of papers on VRP and LRP have considered multi-objective functions [1, 5, 6, 11, 16, 20, 38]. Having a more meticulous outlook, about 89% of routing papers considering only one optimization objective mainly concentrated on economic aspects [38]. Besides, the number of papers with numerous objective functions in 2E-LRP is very rare [20].
- About 31% of related papers used exact methods and, instead, others proposed heuristics or metaheuristics to solve the problem [38]; however, due to the maturity of existing exact and heuristic/metaheuristic methods and a plethora of new hybrid methods of such approaches, researchers are able to cope with larger instances in exact solution approaches rather than those previous ones [6, 16].
- There is a meaningful trend towards considering more comprehensive and integrated problems by taking numerous real-life variants into account to make models more practical, even though formulation and solution of such rich problems are, in turn, more difficult [5, 6, 16, 38].

Therefore, the main goal of this paper can be summarized as follows:

- Proposing a special case of 2E-LRP in a cash-in-transit sector combining multiple real-life variants, such as multi-echelon, multi-period, capacitated vehicles and distribution centers, different time windows and different conflict objective functions, to tackle realistic problems. Then, a mathematical mixed-integer linear programming for this rich LRP is formulated. To the best of our knowledge, this is the first mandatory step to apply the model in real-life problems and, on the other hand, a model with just few constraints even with the best solution approaches cannot be applicable to real-world problems.
- Exploiting a solution approach for optimizing the multi-objective mixed integer linear problem with large integer coefficients in order to find the location and number of intermediate facilities among candidate ones, the number of vehicles in each type and echelon, the amount of commodities received from the Central Bank and delivered to open logistics center and bank branches/ATMs.

3. Problem Description and Mathematical Model

In classical 2E-LRP, a vehicle picks up the freight from the first stage (i.e., depots) and delivers it to the second stage (i.e., intermediate facilities) where operations such as storage, integration or consolidation occur and, then, return to its origin. Then, another vehicle starts its tour from the second stage and returns to its origin after delivering the freight to the third stage (i.e., customers).

Cash distribution in the banking sector for satisfying the customers' needs of physical currency such as coins and banknotes is a special case of 2E-LRP with various variants in routing coupled with numerous assumptions and constraints as well as ordinary concerns of the transportation cost and risk. In this problem, as illustrated in Fig. 1, a vehicle tour is started from the second stage at a distribution center (called also logistics center), instead of movement from the first stage. In the first echelon, an empty armored vehicle named primary vehicle located in one of the candidate logistics centers moves directly to the Central Bank, which is a pre-known single location in the first stage, receives the physical currency, and returns to the origin after distributing among intermediate facilities. In the second echelon, another armored vehicle called secondary vehicle transports the commodities to the customers (bank branches/ ATMs) and returns to the original logistics center. This operation takes place daily with respect to the many constraints such as capacity and time window (detailed assumptions are given in subsection 3.1).

To benefit from formulation of such a real-world problem and make it more applicable, initially, a comprehensive mathematical model that simultaneously considers all variants and characteristics, such as discrete time periods, heterogeneous fleets, capacitated vehicles, and different time windows, is required. Thus, this paper proposes a mathematical programming for a rich problem of multi-echelon, multi-period, capacitated single depot location-routing problem with time windows, and different conflict objective functions (BO-2E-PCLRPSD-TW, from now on). This research

also aims to find the location and number of intermediate facilities among candidate ones, the amount of commodities received from the Central Bank and delivered to facilities in each period, and the best routes providing the minimum transportation cost and risk.

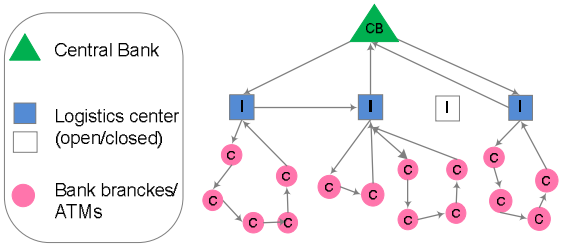

Fig. 1. The structure of 2E-LRP in CIT sector

The BO-2E-PCLRPSD-TW is defined in a graph G=(N, A), where N is a set of nodes and A is a set of arcs. The node set N is composed by a set of Central Bank, {0}, candidate logistics centers, l, and bank branches/ATMs as customers, c. Set N is partitioned into {N_1, N_2}, where N_1 is a set of Central Bank and candidate logistics centers in the first echelon and N_2 is a set of candidate logistics centers and customers in the second echelon. $A = \{(i,j): i,j \in N\}$ is the set of arcs. Each arc (i, j) has a nonnegative cost c_{ij} mainly based on the real distance between i and j.

In this regard, assumptions, indices, parameters, and variables used in the proposed model are as follows:

3-1. Assumption

- Number of customers and their demands in each period are known;
- Each customer is visited at most once in each time period;
- Customer c may have demands in each period;
- Demands of customers must be satisfied;
- There are different types of vehicles with different capacities belonging to each specific echelon. Cash should be delivered to the ATMS in banknote boxes requiring more space and, in turn, occupying larger space of vehicles;
- Only one vehicle is used in each route to serve the open logistics center or customer needed to be served;
- Primary facility cannot send goods directly to the customers;
- A stretch of each period is considered daily over a five-day planning horizon;
- In the first echelon, trip must begin/end at the same open logistics center so that an armored vehicle can move from logistics center l to the Central Bank, receive cash, and return to its origin. In this tour, after visiting a central bank and before returning to the origin logistics center, other logistics facilities can be visited;
- Second echelon trip must begin/end at same open logistics center while distributing the banknote to the customers;
- Time windows of all nodes should be respected;
- Intermediate facilities have different time windows in the first and second echelons;
- Each type of vehicles has its limited capacity;
- Each logistics center has a limited capacity of cash handling;
- Each logistics center has a limited number of parking spaces for vehicles;
- There is no need to use all vehicles in each period;
- Shortage is not allowed; instead, storage is allowed;
- The commodity cannot be moved from Central bank to the customers directly;
- The average duration and cost between arc (i, j) are known.

3-2. Indices

k Set of vehicle type, k= {1, …, K}

m_k Set of number of vehicles with type k, m_k= {1, …, M_k}

l Set of candidate Logistics center, l= {1, …, L}

c Set of customers, c= {1, …,C}

T Set of length of planning horizon with discrete time period, l= {t, …,T}

3-3. Parameters

ON_l	Opening cost of Logistics center l
c_{ij}	Average cost of travelling from node i to node j
OV^k	Operation cost of each vehicle of type k
OC_t	Opportunity cost in time period t
r_{ij}	Risk of travelling from node i to j
Q^k	Capacity of each vehicle of type k
HC_l	Capacity of commodity handling in Logistics center l
CAP_c	Capacity of inventory holding at each bank branch/ATM as customer c
PC_l	Parking capacity of each logistic center l (fleet size)
tt_{ijt}	Average travel time from node i to node j in time period t
st_{it}	Average service time for each node i in time period t
d_{ct}	Demand of customer c in time period t
$[ef_{it}, lf_{it}]$	Time window constraint for node i in the first echelon in time period t
$[es_{it}, ls_{it}]$	Time window constraint for node i in second echelon in time period t
$L_{\max}$	Maximum number of opened Logistics centers

3-4. Decision variables

Binary variables are as follows:

$$x_{ijt}^{m_k k} = \begin{cases} 1 & \text{if vehicle } m_k \text{ of type k traverses arc } (i,j) \in N_1 \\ & \text{in time period t} \\ 0 & \text{otherwise} \end{cases}$$

$$f_{lt}^{m_k k} = \begin{cases} 1 & \text{if vehicle } m_k \text{ of type } k \text{ visit Logistics center } l \in L \\ & \text{in the first echelon in time period } t \\ 0 & \text{otherwise} \end{cases}$$

$$h_{ijt}^{m_k k} = \begin{cases} 1 & \text{if vehicle } m_k \text{ of type k traverses arc } (i,j) \in N_2 \text{ in} \\ & \text{time period } t \\ 0 & \text{otherwise} \end{cases}$$

$$g_{ct}^{m_k k} = \begin{cases} 1 & \text{if vehicle } m_k \text{ of type } k \text{ visit customer } c \in C \text{ in the} \\ & \text{second echelon in time period } t \\ 0 & \text{otherwise} \end{cases}$$

$$y_l = \begin{cases} 1 & \text{if Logistics center } l \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$$

$$\gamma_{lct} = \begin{cases} 1 & \text{if Logistics center } l \text{ serves customer } c \text{ in time} \\ & \text{period } t \\ 0 & \text{otherwise} \end{cases}$$

Other decision variables:

$\alpha_{lt}^{m_k k}$ The amount of commodity delivered to secondary facility (Logistics center) l by vehicle m_k of type of k in time period t

$\beta_{ct}^{m_k k}$ The amount of commodity delivered to customer c by vehicle m_k of type of k in time period t

I_{lt} Inventory level at secondary facility l at the end of period t

I_{ct} Inventory level of customer c at the end of period t

$tf_{it}^{m_k k}$ Arrival time of each primary vehicle to node $i \in N_1$ in time period t

$ts_{it}^{m_k k}$ Arrival time of each secondary vehicle to node $i \in N_2$ in time period t

3-5. Mathematical formulation

Regarding these notations, the BO-2E-PCLRPSD-TW is formulated as follows:

$$Min\, Z_1 = \sum_{l\in L} ON_l y_l + \sum_{t\in T}\Big(\sum_{k\in K_1}\sum_{m_k\in M_{K_1}}\sum_{i,j\in N_1} c_{ij} x_{ijt}^{m_k k} + \sum_{k\in K_2}\sum_{m_k\in M_{K_2}}\sum_{i,j\in N_2} c_{ij} h_{ijt}^{m_k k} + \sum_{l\in L}\sum_{k\in K_1}\sum_{m_k\in K_1} OV^k x_{l0t}^{m_k k} + \sum_{l\in L}\sum_{c\in C}\sum_{k\in K_2}\sum_{m_k\in M_{K_2}} OV^k h_{lct}^{m_k k} + OP_t\Big(\sum_{l\in L} I_{lt} + \sum_{c\in C} I_{ct}\Big)\Big) \quad (1)$$

$$Min\, Z_2 = \sum_{t\in T}\Big(\sum_{k\in K_1}\sum_{m_k\in M_{K_1}}\sum_{i,j\in N_1} r_{ij} x_{ijt}^{m_k k} + \sum_{k\in K_2}\sum_{m_k\in M_{K_2}}\sum_{i,j\in N_2} r_{ij} h_{ijt}^{m_k k}\Big) \quad (2)$$

subject to

$$\sum_{i\in N_2} h_{ict}^{m_k k} = \sum_{j\in N_2} h_{cjt}^{m_k k} = g_{ct}^{m_k k} \quad ;c\in C,\ m_k \in M_{K_2},\ k\in K_2,\ t\in T \quad (3)$$

$$\sum_{k\in K_2}\sum_{m_k\in M_{K_2}}\sum_{\substack{i\in N_2\\ i\neq c}} h_{ict}^{m_k k} \le 1 \quad ;\forall c\in C,\ t\in T \quad (4)$$

$$\sum_{i\in L}\sum_{j\in C} h_{ijt}^{m_k k} \le 1 \quad ;\forall m_k \in M_{K_2},\ k\in K_2,\ t\in T \quad (5)$$

$$\sum_{c\in C}\sum_{k\in K_2}\sum_{m_k\in M_{K_2}} h_{lct}^{m_k k} \le y_l M \quad ;\forall l\in L,\ t\in T \quad (6)$$

$$\sum_{c\in C}\sum_{k\in K_2}\sum_{m_k\in M_{K_2}} h_{lct}^{m_k k} \ge 1-(1-y_l)M \quad ;\forall l\in L,\ t\in T \quad (7)$$

$$h_{clt}^{m_k k} \le \gamma_{lct} \quad ;\forall l\in L,\ c\in C,\ m_k\in M_{K_2},\ k\in K_2,\ t\in T \quad (8)$$

$$h_{lct}^{m_k k} \le \gamma_{lct} \quad ;\forall l\in L,\ c\in C,\ m_k\in M_{K_2},\ k\in K_2,\ t\in T \quad (9)$$

$$h_{ijt}^{m_k k} + \gamma_{lit} + \sum_{\substack{l'\in L\\ l'\neq l}} \gamma_{l'jt} \le 2 \quad ;\forall l,l'\in L,\ i,j\in C,\ i\neq j,\ m_k\in M_{K_2},\ k\in K_2,\ t\in T \quad (10)$$

$$\sum_{l} \gamma_{lct} = 1 \quad ;\forall c\in C,\ t\in T \quad (11)$$

$$\sum_{i\in C'}\sum_{j\in C'} h_{ijt}^{m_k k} \le |C'|-1 \quad ;\forall |C'|\subseteq C,\ |C'|\ge 2,\ m_k\in M_{K_2},\ k\in K_2,\ t\in T \quad (12)$$

$$\beta_{ct}^{m_k k} \le Q^k \times \sum_{i \in N_2} h_{ict}^{m_k k} \quad ; c \in C,\ m_k \in M_{K_2},\ k \in K_2,\ t \in T \tag{13}$$

$$\sum_{i \in N_2} \sum_{c \in C} \beta_{ct}^{m_k k} \le Q^k \quad ; m_k \in M_{K_2},\ k \in K_2,\ t \in T \tag{14}$$

$$\sum_{c \in C} d_{ct} \gamma_{lct} \le HC_l y_l \quad ; l \in L,\ t \in T \tag{15}$$

$$I_{ct} \le CAP_c \quad ; \forall c \in C,\ t \in T \tag{16}$$

$$I_{ct} = I_{ct-1} + \sum_{k \in K_2} \sum_{m_k \in M_{K_2}} \beta_{ct}^{m_k k} - d_{ct} \quad ; \forall c \in C,\ t \in T \tag{17}$$

$$ts_{it}^{m_k k} + s_{it} + tt_{ijt} - M(1 - h_{ijt}^{m_k k}) \le ts_{jt}^{m_k k} \quad ; \forall i \in C, j \in N_2, m_k \in M_{K_2},\ k \in K_2,\ t \in T \tag{18}$$

$$tt_{ijt} - M(1 - h_{ijt}^{m_k k}) \le ts_{jt}^{m_k k} \quad ; \forall i \in L, j \in N_2,\ m_k \in M_{K_2},\ k \in K_2, t \in T \tag{19}$$

$$g_{it}^{m_k k}\, es_{it} \le ts_{it}^{m_k k} \le g_{it}^{m_k k}\, ls_{it} \quad ; \forall i \in N_2,\ m_k \in M_{K_2},\ k \in K_2,\ t \in T \tag{20}$$

$$\sum_{k \in K_1} \sum_{m_k \in M_{K_1}} f_{lt}^{m_k k} + \sum_{k \in K_2} \sum_{m_k \in M_{K_2}} g_{lt}^{m_k k} \le PC_l \quad ; \forall l \in L,\ t \in T \tag{21}$$

$$\sum_{j \in N_1} x_{jit}^{m_k k} = \sum_{j \in N_1} x_{ijt}^{m_k k} = f_{it}^{m_k k} \quad ; \forall i \in N_1,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{22}$$

$$x_{l0t}^{m_k k} = \sum_{i \in N_1} x_{ilt}^{m_k k} \quad ; l \in L,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{23}$$

$$\sum_{i \in N_1'} \sum_{\substack{j \in N_1' \\ j \ne i}} x_{ijt}^{m_k k} \le \left|N_1'\right| - 1 \quad ; \forall \left|N_1'\right| \subseteq N_1,\ \left|N_1'\right| \ge 2,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{24}$$

$$\sum_{i \in N_1} \sum_{k \in K_1} \sum_{m_k \in M_{K_1}} x_{ilt}^{m_k k} \le M y_l \quad ; \forall l \in L,\ t \in T \tag{25}$$

$$\sum_{i \in N_1} \sum_{k \in K_1} \sum_{m_k \in M_{K_1}} x_{ilt}^{m_k k} \ge 1 - M(1 - y_l) \quad ; \forall l \in L,\ t \in T \tag{26}$$

$$\sum_{l \in L} y_l \le L_{\max} \tag{27}$$

$$\alpha_{lt}^{m_k k} \le HC_l\, y_l \quad ; \forall l \in L,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{28}$$

$$\alpha_{lt}^{m_k k} \le Q^k \times \sum_{i \in N_1} x_{ilt}^{m_k k} \quad ; l \in L,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{29}$$

$$\sum_{i \in N_1} \sum_{l \in L} \alpha_{lt}^{m_k k} \le Q^k \quad ; m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{30}$$

$$I_{lt} = I_{lt-1} + \sum_{k \in K_1} \sum_{m_k \in M_{K_1}} \alpha_{lt}^{m_k k} - \sum_{c \in C} \sum_{k \in K_2} \sum_{m_k \in M_{K_2}} \beta_{ct}^{m_k k} \gamma_{lct} \quad ; \forall l \in L,\ t \in T \tag{31}$$

$$tf_{it}^{m_k k} + s_{it} + tt_{ijt} - M(1 - x_{ijt}^{m_k k}) \le tf_{jt}^{m_k k} \quad ; \forall i, j \in N_1,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{32}$$

$$tt_{i0t} - M(1 - x_{i0t}^{m_k k}) \le tf_{0t}^{m_k k} \quad ;\forall i \in L,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{33}$$

$$g_{it}^{m_k k}\, ef_{it} \le tf_{it}^{m_k k} \le g_{it}^{m_k k}\, lf_{it} \quad ;\forall i \in N_1,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{34}$$

$$x_{ijt}^{m_k k}, f_{lt}^{m_k k}, y_l \in \{0,1\} \quad ;\forall i, j \in N_1,\ l \in L,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{35}$$

$$h_{ijt}^{m_k k},\ g_{ct}^{m_k k}, \gamma_{lct} \in \{0,1\} \quad ;\forall i, j \in N_2,\ c \in C,\ l \in L,\ m_k \in M_{K_2},\ k \in K_2,\ t \in T \tag{36}$$

$$\alpha_{lt}^{m_k k}, I_{lt},\ tf_{it}^{m_k k} \ge 0 \quad ;\forall l \in L,\ i \in N_1,\ m_k \in M_{K_1},\ k \in K_1,\ t \in T \tag{37}$$

$$\beta_{ct}^{m_k k},\ I_{ct},\ ts_{it}^{m_k k} \ge 0 \quad ;\forall c \in C,\ i \in N_2,\ m_k \in M_{K_2},\ k \in K_2,\ t \in T \tag{38}$$

This problem involves two-conflict objective functions simultaneously: (1) minimization of total cost and (2) minimization of transportation risk. The objective function (1) measures the total cost of the model composed of six parts. The first term is the effective cost of opening logistics centers over a planning horizon. The subsequent two terms are transportation costs in the first and second echelons, respectively. The fourth and fifth summations are associated with total operation cost of vehicles in case of using in each period. The final term denotes the opportunity cost regarding the inventories in logistics centers and bank branches/ATMs. The objective function (2) minimizes the total transportation risk in both echelons.

Constraints (3) to (20) are associated with the second echelons. In constraint (3), flow conservation for each customer in each time period is expressed. Constraint (4) ensures that each customer visits at most once in each day. Inequality (5) imposes a limitation that each armored vehicle in the second echelon leave, at most, one logistics center. Constraints (6) and (7) assure that if a candidate logistics center is open, at least one vehicle moves from that facility center toward a customer. Three inequalities (8)-(10) forbid illegal routes in the second echelons which do not start and end at the same logistics center, and guarantees that a vehicle returns to its distribution center of origin. Constraint (11) enforces that a customer is assigned to a single logistics center. Sub-tour elimination in the second echelon is expressed in inequality (12). Constraints (13)-(16) are related to capacity inequalities. Constraint (13) prohibits delivering of commodity by vehicle m_k of type k to a customer if such a vehicle does not visit that customer. Constraint (14) guarantees that the total amount of commodities carried by a vehicle should not exceed the vehicle capacity. Constraint (15) expresses that if a logistics center is closed, no customer is assigned to it; otherwise, the customers' total required commodities satisfied by an open logistics center should respect the handling capacity of the origin. Capacity inequality associated with the inventory held in each bank branch/ATM is expressed in constraint (16), and, inventory balance of each customer in each time period is described in equation (17). Constraints (18) and (19) state a relationship between the arrival times of a secondary vehicle at consecutive stopes in a tour. Constraint (20) imposes the time window restrictions on any node in the second echelon. Constraint (21) assures that the total number of vehicles used in both first and second echelons should not exceed the capacity of parking spaces at each logistics center. The remaining constraints are associated with the first echelon. Constraints (22) show the flow conservation at each logistics center in each time period. Constraint (23) imposes a limitation that if a vehicle moves the logistics center toward the Central Bank, it must return to the original location while it also can serve other logistics centers. Inequality (24) ensures the sub-tour elimination in the first echelon. Constraints (25) and (26) require that if a candidate logistics center is open, at least one vehicle

enters to that facility center. The maximum number of logistics center to be opened is given in constraint (27). Constraints (28)-(29) are related to the vehicles capacity, and constraint (30) is associated with the handling capacity in the first echelon. The former inequality imposes a restriction such that, in each time period, if no vehicle visits a logistics center, consequently, no commodity is delivered to that intermediate facility center. Constraint (29) states the total amount of commodities delivered from Central bank should not exceed the vehicle capacity. Constraint (30) assures that if a logistics center is open, the total amount of commodities delivered to that facility center should respect its handling capacity. Equation (31) imposes the inventory balance of each logistics center in each time period. Constraints (32) and (33) state a relationship between the arrival times of a primary vehicle at two consecutive nodes, and inequality (34) ensures that a vehicle should reach at any node within an allowed time window. Finally, Constraint (35) to (38) specify a range of the variables.

Formulation is nonlinear because of constraints (31). However, the constraint can be rewritten using a set of linear constraints as follows:

Linearizing constraint (31):

$$I_{lt} = I_{lt-1} + \sum_{k\in K_1}\sum_{m_k\in M_{K_1}} \alpha_{lt}^{m_k k} - \sum_{c\in C}\sum_{k\in K_2}\sum_{m_k\in M_{K_2}} \omega_{ct}^{m_k k} \quad ;\forall l\in L,\ t\in T,\ t>1 \tag{39}$$

$$\omega_{lct}^{m_k k} \le M\,\gamma_{lct} \quad ;\forall l\in L,\ c\in C,\ m_k\in M_{K_2},\ k\in K_2,\ t\in T \tag{40}$$

$$\omega_{lct}^{m_k k} \le \beta_{ct}^{m_k k} \quad ;\forall l\in L,\ c\in C,\ m_k\in M_{K_2},\ k\in K_2,\ t\in T \tag{41}$$

$$\omega_{lct}^{m_k k} \ge \beta_{ct}^{m_k k} - M(1-\gamma_{lct}) \quad ;\forall l\in L,\ c\in C,\ m_k\in M_{K_2},\ k\in K_2,\ t\in T \tag{42}$$

The goal is to simultaneously minimize the total travel cost and reduce the relative total risk of vehicle routes.

4. Multi-Objective Optimization Method

In the multi-objective optimization problem (MOOP), there is no single optimal solution being able to optimize all the objective functions concurrently; instead, there are several objective functions and DMs should find the "most preferred" solution. The Pareto optimal solutions (named also non-dominated, non-inferior, efficient solutions) are ones with the property that it is impossible to improve the value of one objective function without weakening the performance of at least one other objective function. The small number of efficient solutions produces the trade-off surface or Pareto front; under such circumstances, the DM should intervene to make the best compromise solution among the presented efficient solutions.

Exact methods can be categorized into three following classes in which DMs can interfere and express the preferences over the objectives [Hwang-MO]:

- Priori methods: the DMs give the preferences (i.e., weights) in advance.
- Interactive methods: the DMs preferences are expressed during the solution procedure.
- Generation/Posteriori methods: the DMs express their preferences after discovering the Pareto set.

In the first two methods, DMs are called to express the preferences while they do not have the Pareto front; however, generation methods deal with this issue and, after having the required information, the DMs make the ultimate choice.

Among several classical generation methods being able to solve MOOPs by generating representations of the Pareto front, the weighted sum and the ε-constraint methods are the most famous techniques. However, the latter outperforms especially in the problems with discrete variables in the pure integer or mixed integer problems. One of the superiorities is that there is no need to provide scaling of the objective functions that can

affect the results in the ε-constraint method, while any method summing up diverse objectives requires scaling factors, even though the variables are normalized. The interested reader is referred to [39].

4-1. AUGMECON2 method

One of the best approaches to solving multi-objective problems is the ε-constraint method [40]. In this method, typically, the objective function with the high priority is considered as an objective function, and the rest must be transformed to equalities by considering a constraint vector ε. The classical ε-constraint method has three weak points in its implementation that is addressed in new version named AUGMECON as follows [39]:

- The calculation of the range of the objective functions over the efficient set: in the ordinary method, the best value is considered as the optimal value of the separate optimization, and the nadir value is approximated with the worst of the corresponding column; however, AUGMECON benefits from the lexicographic optimization to create the payoff table with only Pareto-optimal solutions.
- The guarantee of efficiency of the obtained solution: to do so, by combining the appropriate slack/surplus variables, the objective function constraints are converted into model constraints. Such slack/surplus variables are used as the second term, with lower priority in a lexicographic manner, in the objective function, imposed to provide only efficient solutions.
- The increased solution time for problems, especially in problems with more than two objective functions: it is addressed by incorporating acceleration issues (i.e., early exit from the loops).

AUGMECON2 is the improved version of the augmented ε-constraint [41]. This method, by introducing a bypass coefficient, outperforms the previous version, especially in the larger data set with larger integer coefficients for the objective functions. The AUGMECON2, specifically, provides the exact Pareto set in multi-objective integer programing problems by properly tuning its running parameters. Not only is this one of the best available exact methods able to solve the MOOPs, but also it is competitive with multi-objective meta-heuristics (MOMH) methods to produce adequate approximations of the Pareto set in multi-objective combinatorial optimization (MOCO) problems, especially in small- and medium-sized instances [41]. The following steps are required to apply the AUGMECON2 in our MOIP problem:

$$\min f_j(x) - eps(\sum_{i=2}^{p} 10^{-(i-2)} \times \frac{S_i}{r_i})$$
$$f_i(x) + S_i = e_i \quad \forall i \neq j$$
$$x \in S,\ S_i \in R^+ \tag{43}$$

where $e_2,\ldots,\ e_p$ are the parameters for the right-hand side (RHS) of the specific iteration on the grid points of the objective functions 2, 3, …, p. Parameters $r_2,\ldots,\ r_p$ are the ranges of the respective objective functions. The slack variables of the respective ε-constraints are $S_2,\ldots,\ S_p$ and the eps $\in [10^{-6}, 10^{-3}]$. This modification in the objective function, compared to AUGMECON, is added to produce a lexicographic order in the rest of the objective functions, if there is any alternative optima. This formulation forces the sequential optimization. To delineate, a solver will find the optimal solution for f_1 and then it will try to optimizef_2 and so on, while the sequence of optimizations of $f_2 - f_p$ in the previous formulation was indifferent.

For each objective function $i=2,\ldots,p$, the objective function range is calculated as the difference between the best and worst values of the payoff table. Then, the range of the i^{th} objective function is divided into q_i equal intervals; thus, there would be total $(q_i + 1)$ grid points used to vary parametrically the RHS e_i of the i^{th} objective function. Therefore, the discretization step for this objective function is given as follows:

$$step_i = \frac{r_i}{q_i} \tag{44}$$

The RHS of the corresponding constraint in the t^{th} iteration in the specific objective function will be as Eq. (45), where f_i^{min} is the worst value from the payoff table and t is the counter for the specific objective function:

$$e_i^t = f_i^{\min} + (step_i \times t) \quad t = 0,\ldots,q_i \tag{45}$$

In each iteration, a slack variable that corresponds to the innermost objective function is checked. In this case, it is the objective

function with p=2. After that, the bypass coefficient is calculated as follows:

$$b = \text{int}(\frac{S_2}{step_2}) \quad (46)$$

In the right-hand side of equation (46), int() is an integer part of a real number. When the slack variable S_2 is larger than $step_2$, in the following iteration, the same solution will be obtained and the only difference is the surplus variable which will have value $S_2 - step_2$. Thus, to avoid the iteration redundant, it can be bypassed as no new Pareto optimal solution is generated. Bypass coefficient b specifies the number of bypassed consecutive iterations. With this approach, AUGMECON2 method significantly improves the solution time, especially when there are many grid points [41].

5. Computational Results

This paper proposes a complex model and a MMILP formulation for a real-life model . To demonstrate the validity of the proposed rich problem and the formulation, a numerical experiment is presented and the related results are shown in this section. We used data stem from a real-world case in one of the Iranian banks for distribution of currency banknotes to some branches located in Tehran. Tab. 1 shows the size of this problem. Moreover, to calculate the risk between nodes, a risk route calculation method proposed in [34] is applied. Finally, parameters c_{ij} and t_{ijt} are calculated based on the real data.

All of the mathematical formulas have been coded in GAMS (General Algebraic Modeling System) and the experiments have been performed on an Intel core i5-3337U, 1.8 GHz processor with 6 GB RAM.

Tab. 1. Size of the sample tests

Scale of problem	Test 1	Test 2	Test 3
No. nodes in the first stage	1	1	1
No. nodes in the second stage	3	3	3
No. nodes in the third stage	10	12	13
No. periods (days)	5	5	5
No. vehicle types in each echelon	2	2	2
No. vehicles in each type in each echelon	2	2	2

To analyze the formulation and the solution method, results of test problem 1 are analyzed in this section. Firstly, the real distance and travel time for travelling an armored vehicle from node i to node j and its associated 14*14 matrix are calculated based on the real data by using Google Map travel distance/time matrix API. Fig. 2 shows the output of the coding for such routes for the first echelon on the google map. For example, the real distance and travel time of matrix element associated with a route between the Central Bank and the third candidate logistics center (l3) are 13.6 km and 34 minutes, respectively.

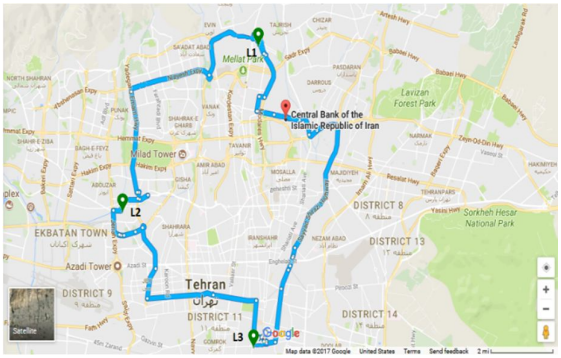

Fig. 2. A visualization of Google Map API and the real travel time/distance among nodes in the first echelon

Then, using the AUGMECON2, the Pareto fronts are obtained. Fig. 3 illustrates the results and demonstrates the conflict between two objective functions value so that, with decreasing the value of the first objective function (i.e., total cost), the second objective function's (i.e., total transportation risk) value is increased, and vice versa. One of the obtained solutions in terms of routes in two echelons is shown schematically in Fig. **4**, which proves the validity of formulation in a proper allocation of facilities to the customers as well as legal tours regarding constraints such as start/end points in each echelon, continuity of the routes, and avoided sub-tours. Fig. **4**(a) depicts the position of all nodes before solving the location-routing (LR) problem, and 4(b) to 4(f) illustrate the solution after solving the problem over a five-day planning horizon.

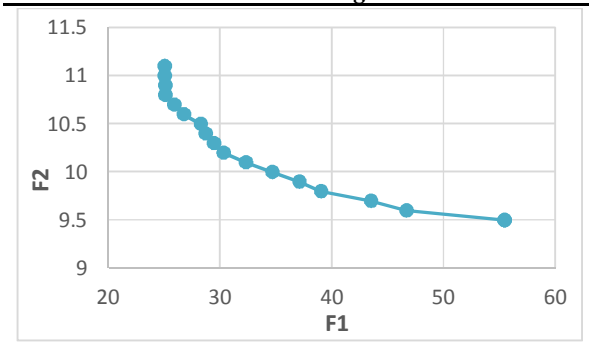

Fig. 3. The Pareto frontiers for test problem 1

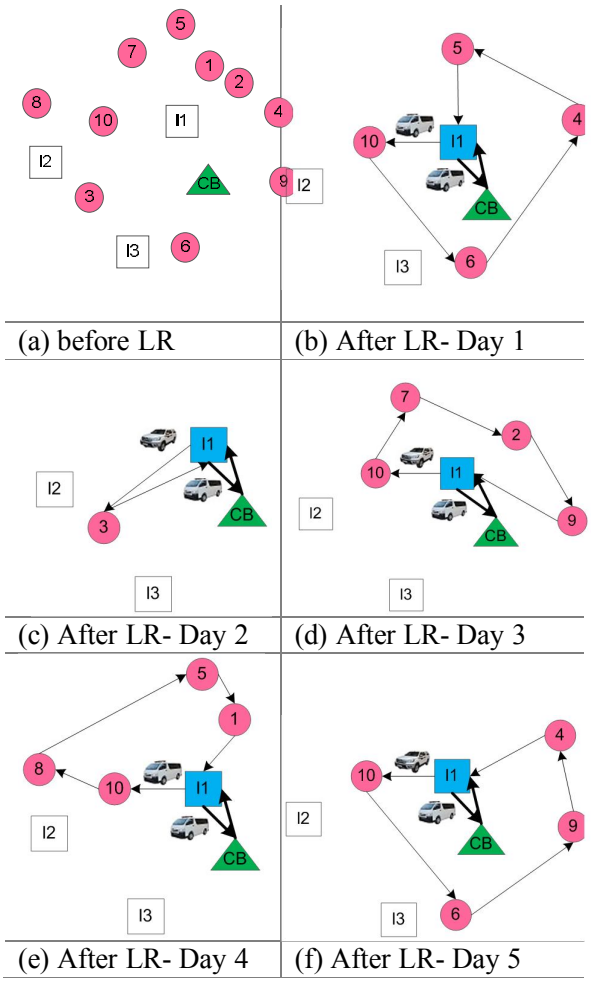

Fig. 4. A schematic view of routes in one of the obtained solutions for test problems 1.

Decision-makers, at this point, should select the ultimate solution among all Pareto solutions considering other probable criteria that are impossible to be calculated. Furthermore, in unforeseeable circumstances such as blocking some routes, it is possible for DMs to choose one other solution with different routes.

6. Conclusion and Future Research

In this paper, a special case of 2E-LRP in a cash-in-transit sector was proposed. Taking the exhaustive literature review papers [5, 6, 16, 38] into consideration, there is a significant trend among researchers to formulate comprehensive and integrated problems to make it more applicable, instead of focusing on sophisticated solution methods for problems containing just few constraints. We adopted this approach and proposed a special case of 2E-LRP in the CIT sector, named BO-2E-PCLRPSD-TW, considering several existing real-life variants simultaneously such as multi-echelon, multi-period, capacitated vehicles, distribution centers and ATMs, different type of vehicles in each echelon, different time windows and different objective functions to tackle this realistic problem. In a CIT problem, distribution of physical currency with the minimum transportation cost and risk is of top priorities among managers. Thus, these two conflicting objective functions were used in our model and the rich and complex model in MMILP was formulated. To validate the suitable formulation and solve the model, the last improved version of ε-constraint named AUGMECON2 was used, which is a very efficient method for solving MOIP and provides the exact Pareto front. Results substantiate the suitability of the model and its formulation. Finally, there are some directions to improve this article in future research. The BO-2E-PCLRPSD-TW problem can be extended with other real-life variants such as forbidden region, route length restrictions, fuzzy/stochastic parameters, time-dependent networks, precedence relations, integration of locations and revenue management. Moreover, other risk indexes can be developed considering travel time between nodes, amount of commodities transferred by vehicles and peripatetic routes. At the end, even though AUGMECON2 is very competitive even with MOMH methods in small- and medium-sized problems, there is a need for heuristic or metaheuristic approaches for solving the problem in large-scale instances, making it a very complex problem.

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