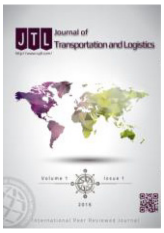

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JTL

Journal of Transportation and Logistics
7 (2) 2022

İSTANBUL UNIVERSITY PRESS

DOI: 10.26650/JTL.2022.1113726

RESEARCH ARTICLE

A Multi Depot Multi Product Split Delivery Vehicle Routing Problem with Time Windows: A Real Cash in Transit Problem Application in Istanbul, Turkey

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ABSTRACT

In today's highly competitive world market, companies and private enterprises deliver their business on time. Their value and total costs play an essential role in their positions in the market. The most costly and difficult factors to regulate are shipping and distribution systems. The high cost of transportation and distribution systems is one reason for the increase in vehicle routing problems and studies in logistics network design. Vehicle routing problems (VRPs) are concerned with finding the optimal or near-optimal routes for vehicles to follow in meeting the demands of customers or facilities. The cash in transit (CIT) problem as a version of the VRP, deals with the planning of money distribution from the depot(s) to Automated Teller Machines (ATMs) safely and quickly. This paper investigates a novel CIT problem, which is a variant of split delivery VRP with time windows. To establish a novel approach to the CIT problem, different money currencies are considered. Also, multiple depots and heterogeneous fleet are included in the problem. To handle the CIT problem more realistically, a risk constrained multi-depot multi-product heterogeneous fleet split delivery VRP with a time windows formulation is proposed. The problem is hence formulated as a mixed-integer mathematical model. The mathematical model is run for different scenarios and optimal routes are obtained. The experimental analysis shows that the mathematical model developed, can help decision-makers to obtain effective solutions for their CIT operations with different money currencies.

Keywords: Vehicle Routing Problem, Cash-In Transit, Split-Delivery, Istanbul

Submitted: 08.05.2022 • **Revision Requested:** 20.07.2021 • **Last Revision Received:** 22.07.2022 • **Accepted:** 17.08.2022

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Citation: Ayyildiz, E., Sahin, M.C., & Taskin, A. (2022). A multi depot multi product split delivery vehicle routing problem with time windows: A real cash in transit problem application in Istanbul, Turkey. *Journal of Transportation and Logistics, 7*(2), 213-232. https://doi.org/10.26650/JTL.2022.1113726

1. The Cash in Transit Problem

The cash transportation problem has not received much attention in the literature, and there are few studies focusing on this problem. One of the key reasons why robberies are so common is the lack of security analysis during the route planning process (Hepenstal & Johnson, 2010). CIT operations should be carefully planned in case of theft. Banks' cash management is of great interest due to significant changes in interest rates and the availability of funds, particularly during periods of recession. This emphasis on cash management is prompted, in part, by the relatively low cost of cash management costs compared to general banking costs, and in part by a cost effective process due to increased liquidity in times of a liquidity crunch (Ágoston, Benedek, & Gilányi, 2016). CIT transport activities include the receipt, transportation, and distribution from payment centers, bank branches, ATMs, jewelers, and retail stores of valuables (i.e., cash, shares, jewelry, and other financial instruments). Financial companies, such as banks, exchange offices, jewelers, major supermarket stores, etc., perform CIT operations. Such services are requested by businesses that process large amounts of cash and other valuables daily (Bozkaya, Salman, & Telciler, 2017). However, following the global economic downturn, the volume of cash in circulation worldwide has risen annually and continues to play an important role in recent decades. Cash sales globally were valued at $11.6 trillion in 2012, with a 1.75 percent increase between 2008 and 2012. The CIT business, banknotes, coins and valuables are used for this purpose. In general, cash and valuables are exchanged between consumers and one or more cash depositors or institutions, usually via ground vehicles (armored or unarmored) (Talarico, 2016).

Crime is a major concern due to the nature of the items being carried, and CIT carriers are constantly vulnerable to serious security risks such as theft and gun attacks. Attacks on CIT instruments are certainly not uncommon, but the number of incidents, risk ratios and average casualties differ by region. The United Kingdom is the European country with the most attacks on cash carriers and the highest risk ratio and casualty statistics. In 2008, there were over 1,000 confirmed attacks against CIT carriers (Talarico, Sörensen, & Springael, 2015). Vehicle routing and timing for cash transportation are critical for security carriers to reduce operating costs and ensure safe cash delivery (Yan, Wang, & Wu, 2012). It is vital to develop strategies to better avoid the outbreak of robbery. Cash transport companies supply cash, valuable documents, precious metals and other items used by the banking and finance industries. It provides storage, counting and custody services for these institutions' shares and payment system equipment. Cash transport companies are responsible for the relevant value within the time it takes to deliver the money and value it receives. The CIT company is primarily responsible for the losses that may occur in the assets transported and stored within the liability period specified as a trap in the sector. For this reason, cash transportation companies have arranged all their operation processes, the containers they use in transportation, to protect the value of vehicles and buildings. Armored vehicles are equipped with different armor levels according to the risk of the mission. The cash counting centers where cash is stored have been designed and built to meet the needs in terms of architecture and construction. Up-to-date electronic protection and detection systems are used in armored vehicles, and cash counting and cashing centers. In this respect, cash transportation companies stand out as businesses that constantly invest in security systems. To maximize cash conveyance protection in actual activities, regular cash transportation vehicle routes and schedules must vary significantly, making certain vehicle routes and schedules challenging to formulate.

Boonsam et al. consider a case study on the application of techniques for solving an assignment problem (AP) and a vehicle routing problem with time windows (VRPTW) that occurred in the cash distribution of a bank in Bangkok, Thailand (Boonsam, Suthikarnnarunai, & Chitphaiboon, 2011). Michallet et al. address a periodic VRPTW submitted by a software company specialized in transportation problems with security constraints. The hours of visits to each customer over the planning horizon must be spread in the customer's time window (Michallet, Prins, Amodeo, Yalaoui, & Vitry, 2014). Van Anholt et al. introduce the model and solve a rich multi-period inventory-routing problem with pick-ups and deliveries motivated by replenishing ATMs in the Netherlands (Van Anholt, Coelho, Laporte, & Vis, 2016). Larrain et al. model rich and challenging VRP, called the inventory-routing problem with cassettes and stockouts, as the inventory-routing problem (Larrain, Coelho, & Cataldo, 2017). Tarantilis and Kiranoudis present a decision support system (DSS) that uses an intelligent metaheuristic approach and exploits risk methodologies and spatial data information to allow logistics planners to design safe intra-city distribution routes. The DSS routes reduce the likelihood of a profitable vehicle burglary at a certain point on the road network while still satisfying all the operating constraints of the delivery problem (Tarantilis & Kiranoudis, 2004). Sorensen et al. present a version of the VRP to improve protection in the CIT market. A particular index is used to measure the vulnerability of a vehicle to the possibility of being stolen along its path (Talarico, Sörensen, & Springael, 2017). Ghannadpoır and Zandiyeh aim to develop a model for solving VRP with two objective functions; risk minimization and distance minimization to optimize the safety of cash/valuable commodities transportation (Ghannadpour & Zandiyeh, 2020).

In the CIT problem handled in this study, most of the ATMs contain different currencies. Some regions with more tourists and these people need more global currencies. In other words, their amounts vary for each location. Some of them require more global currencies, while others require the main currency of the country. Furthermore, banks take certain constraints into account when transporting money to ATMs. One of them is the time window. Banks define the time intervals for each ATM that money can be delivered to the ATM. This time window may also differ between ATMs. This difference may vary according to the ATM location, the population density of the region, traffic density and transportation networks. In the problem discussed, the allocation of money to each ATM must be between the starting and ending times of the time window. The vehicle arriving at the ATM early will have to wait until the starting time of the ATM's time window. However, due to parking problems at some ATMs, waiting is not allowed. So, it reduces the flexibility of the vehicles while avoiding risks. With split delivery, some vehicles deliver some money and go for the further deliveries, and others can top up the rest of the money. With this feature, vehicles have more flexibility in creating their routes at cheaper costs. The traveling time of the vehicle depends on the location of the ATM/

depot. So, if there is more than one depot, the vehicle could be more flexible regarding the cheaper route and avoid risks during delivery.

This paper's main contributions can be summarized as follows: (1) With multi-product features, the ATMs' demands become more realistic. (2) The split delivery and multi depot problem becomes more complex and allows the vehicles more flexibility. (3) Since the products inside the vehicle are valuable, there is some risk of theft, so with this problem, the vehicles avoid the risks while creating their routes. (5) A new mathematical formulation for the novel CIT problem is presented. (6) Money distribution routes are created for different numbers and types of vehicles.

This study is organized as follows: the basic explanations for VRP are given in Section 2. In Section 3, the proposed methodology to obtain the optimal route(s) is explained. The results are presented and discussed through a sensitivity analysis in Section 4. The last section shows the conclusions and future recommendations.

2. Vehicle Routing Problem

The VRP, in its simplest and general form, is a routing problem in which the constraints are taken into account in order to provide a full service to customers and at the same time it aims to minimize the cost. Dantzig and Ramser proposed the first VRP model in 1959 (Dantzig & Ramser, 1959). The problem can be described as "the design of a set of minimum cost vehicle routes that start and end from a central warehouse for a fleet of vehicles while serving a range of customers". The VRP is a model that serves a set of customers in multiple vehicles in one or more warehouses. It is concerned with finding the most fitting routes for its fleet. The challenge is designing the lowest priced routes for vehicles with complex constraint sets. The definitions of costs can differ from one situation to another. The expense description can vary from one situation to another, but the total distance of vehicles is considered as the objective function in the simplest case. While a pure routing problem has only a regional component, a timing element and a time component require more practical considerations.

In the first proposed VRP model, the homogeneous vehicles supply services/products to customers using the available resources of a depot. The vehicles are identical, have the same capacity and speed (homogeneous fleet). Each customer has a demand and this demand must be satisfied by vehicles. Additionally, each arc from one node to another (customer and depot) has a transportation cost. These costs usually represent distances, traveling times, or a combination of these factors (Caceres-Cruz, Arias, Guimarans, Riera, & Juan, 2014). The VRP and its extensions are a well-studied research area among academics and researchers. According to problem structures, these extensions deal with certainty (deterministic) and uncertainty (i.e. stochastic, fuzzy, or robust). These issues can include a wide variety of real-life constraints related to time and distance factors, the use of heterogeneous fleets, linkage with inventory and scheduling problems, security conditions, environmental and energy issues, traffic density, and more (Caceres-Cruz et al., 2014).

In VRP, which is encountered during the distribution of goods and services in companies, if various assistance such as consultancy, tracking systems and programming are not received for this problem, this situation causes high costs in some sectors. Due to these very high costs, the practical solution to VRPs is important for companies in reducing their costs. Figure 1 shows an example of a VRP solution.

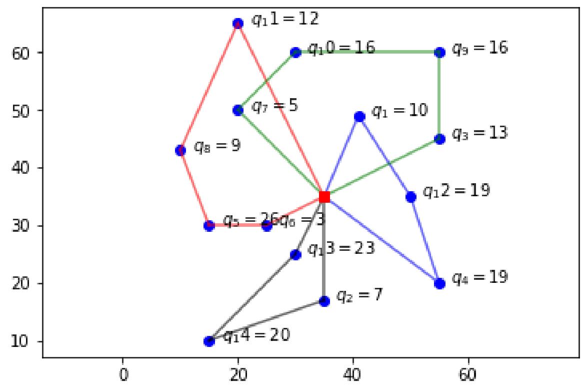

Figure 1: An example of a VRP solution

The topics reviewed are usually more accessible than the challenges of everyday life. Although certain restrictions are omitted, the studies usually model key features and include key findings used in examining and executing real-life problem structures. There are a lot of different variations of VRP. Various types of VRP are available in the literature according to the constraints. The road network, customers, depots, vehicles and drivers are key components of VRP. Different restrictions and situations can be placed on each variable to build various versions of VRP, and each may be necessary to achieve unique goals. We can count these variants as Simple VRP, Capacitated VRP (CVRP), vehicles with capacity, VRP with time windows (VRPTW), and a VRP generalization with additional permissible complication time windows. In these situations, a customer's operation involving the pick-up (delivery) of goods or services, may begin within the time window specified by the earliest and latest times the customer will allow the service to begin (Desrochers, Desrosiers, & Solomon, 1992). A customer must be visited by one vehicle rule is flexible and can be visited by more than one vehicle in Split Delivery VRP (SDVRP) (Archetti & Speranza, 2012). In Multi Depot VRP (MDVRP), each customer is visited by a vehicle-based at one of several depots (Ramos, Gomes, & Barbosa-Póvoa, 2020). In some VRP appiications, the distance to be travelled may be limited for vehicles to be used in routing. Such problems are called Distance Restricted VRP (DCVRP). Periodic VRP (PVRP) is the problem of making the planning period more than one day. Each customer must be visited at least once within the specified period. In VRP with back-haul (VRPB), consumers can demand or return these goods. It is currently an extension of CVRP in which customers are split into two subsets: customers with line-haul and back-haul. In VRP with Pick-up and Delivery, the starting and ending points of the routes are the depots and each customer requests a vehicle, and while this is done, the vehicle capacity cannot exceed the total demand on the route (Goksal, Karaoglan, & Altiparmak, 2013).

Extensions used in this study are briefly described: *Time Window:* The feature that distinguishes the vehicle routing problem with a time window from others is that the customer is visited within a certain time interval. VRPTW is divided into two according to the time interval mentioned. It is a hard VRPTW when the delivery/transaction cannot be made before the specified time interval and a soft VRPTW when the delivery/transaction is carried out, but the penalty cost is incurred when the delivery/transaction is gone (Ho & Haugland, 2004). *Multi Depot Vehicle Routing Problem*: There is only one warehouse for traditional VRP, and all vehicles in that warehouse start and finish their routes. MDVRP has several depots. In this problem, each client in one of several depots is visited by a vehicle (Stodola, 2018). *Split-Delivery Vehicle Routing Problem*: In this VRP type with split demand, more than one vehicle can visit the customer, and the customer demand can be divided. Since one of the purposes is to minimize the cost, if cost reduction is in, VRP may be handled in this way. Some of the remarkable studies in the literature considering the extensions mentioned above are summarized according to the constraints in Table 1.

Table 1. Constraints of some of the remarkable studies

Study	Heterogeneous Fleet	Multi Depot	Split Delivery	Multi Product	Time Window	Risk
(Afshar-Nadjafi & Afshar-Nadjafi, 2017)	Yes	Yes	No	No	Yes	No
(Xu, Wang, & Yang, 2012)	Yes	Yes	No	No	Yes	No
(Yao, Yu, Hu, Gao, & Zhang, 2016)	Yes	No	No	No	No	No
(Levy, Sundar, & Rathinam, 2014)	Yes	Yes	Yes	No	No	No
(Soeanu, Ray, Berger, Boukhtouta, & Debbabi, 2020)	No	Yes	No	No	No	Yes
(Wang et al., 2020)	Yes	Yes	No	No	No	Yes
(Nugroho, Nafisah, Khannan, Mastrisiswadi, & Ramdhani, 2020)	Yes	Yes	Yes	Yes	Yes	No
(Park, Yoo, & Park, 2016)	No	No	Yes	No	Yes	No
(Kaabachi, Jriji, & Krichen, 2017)	No	Yes	No	No	Yes	No
(Sharma & Saini, 2020)	No	Yes	No	No	No	No
This study	Yes	Yes	Yes	Yes	Yes	Yes

Kaabachi et al. propose an advanced meta-heuristic ant colony optimization and local search to resolve the new type of multi-depot heterogeneous VRP with time windows. In this type, the proposed green multi-depot heterogeneous VRP with time windows, they try to optimize the cost of fuel consumption and emission (Kaabachi et al., 2017). Nugroho et al. focus on the distribution of fuel for Premium and Bio-Solar products. In determining the distribution route and distribution time, a heterogeneous fleet, split delivery, multiple products, multiple trips and time windows constraints are considered (Nugroho et al., 2020). Xu et al. solved the multi depot heterogeneous fleet VRP with time windows by constructing and modifying a variable neighborhood search algorithm (Xu et al., 2012).

As a result of the literature research, it is seen that the problem handled in this study is a novel VRP concerning the banking sector. This study deals with the multi-depot, multi-product, heterogeneous fleet, time window and split delivery VRP considering the risk. This study also has a real-life application.

3. Proposed Mathematical Model

The problem is defined on a directed graph expressed as $G = (N,A)$, where N represents the set of nodes and A represents the set of arcs between nodes. The location of each ATM and depot is represented as a node. The index "1" and "2" represent the depot node. The set of arcs defined on $A=\{(i,j):\forall i, j \in N, i\neq j\}$. In this model, P represents the set of products, and each product is represented as set $p \in P$. The problem is given by a set of ATMs J, at different locations. Each connection between location (i, j), where $i \neq j$ and $i, j \in N$ and, has a travel time t_{ij} and a distance traveled C_{ij} that are not symmetrical ($t_{ji} \neq t_{ji}$ and $c_{ji} \neq c_{ji}$) and t_{ij} is nonnegative; denoted by d_{ip} the demand at the point i. The ATM is served from two depots with a limited and heterogeneous fleet. The vehicle has to leave from and return to the depot at the end. There is a set of K of the vehicle with identical capacities for each product. The capacity of each vehicle for each product $k \in V$ is represented by q_{kpi}. There are two different depots, and all depots have the capacity for three products V_{ip}. Each ATM $i \in J$ has a time window, i.e., between $[e_i, l_i]$,, where $e_i \leq l_i$ which means the earliest time of the ATM and the ATM's latest time to start service for ATM i. Let S_i be the service time at ATM i. When the vehicle arrives at the depot, it might be waiting in the parking area for the service time if there is a parking area. More than one vehicle can fulfill the demand of an ATM. This happens in all situations where any demand exceeds the vehicle's capability, but in other cases, it may also be cost-effective. There are robbery risks (r_{ij}) between nodes and the sum of the risks at the used arcs cannot exceed the maximum risk (R)

Set/Indices

N Set of all nodes (depots and ATMs)

j Set of all ATMs

I Set of all depots

P Set of all products

K Set of all vehicles

Q Set of all locations that don't have a parking area

Parameters

M Big Number

m number of ATMs

C_{ij} distance between i and j

d_{ip} the demand of customer i for product p

q_{kp} the capacity of vehicle k for product p

V_{ip} the capacity of depot i for product p

S_i service time for ATM i

e_i earliest service time for ATM i

l_i latest service time for ATM i

r_{ij} risk between i and j

Decision Variables

x_{ijk} 1, if ATM j is supplied after ATM i by vehicle k; 0, otherwise

z_{ij} 1, if ATM j is served from depot i; 0, otherwise

U_{ik} auxiliary variable for sub-tour elimination constraints for vehicle k

β_{jkp} fraction of ATM j's demand p delivered by vehicle k

L_{ik} leaving time for vehicle k at node i

A_{ik} arriving time for vehicle k at node i

W_{ik} waiting time for vehicle k at node i

Formulation

$$\sum_{k\in V}\sum_{i\in N}\sum_{j\in N} x_{ijk}c_{ij} \tag{3.1}$$

The objective of the proposed mathematical model is to minimize the total cost under the following constraints:

$$\sum_{j\in N} d_{ip}\beta_{jkp} \le q_{kp} \qquad \forall k \in K, \forall p \in P \tag{3.2}$$

Constraint (3.2) is a vehicle capacity constraint that guarantees that each product's vehicle capacity is not exceeded.

$$U_{ik} - U_{jk} + mX_{ijk} \le (m-1) \qquad \forall i,j \in J, \forall k \in K \tag{3.3}$$

Constraint (3.3) is a sub-tour elimination constraint.

$$\sum_{j\in N} x_{ijk} - \sum_{j\in N} x_{jik} = 0 \qquad \forall i \in N, \forall k \in K \tag{3.4}$$

Constraint (3.4) is a balance constraint for each node in each of the routes.

$$\sum_{i \in I} \sum_{j \in J} x_{ijk} \leq 1 \qquad \forall k \in K \tag{3.5}$$

Constraint (3.5) provides a vehicle to exit from one depot at the most.

$$\sum_{j \in J} d_{ip} z_{ij} \leq V_{ip} \qquad \forall i \in I, \forall p \in P \tag{3.6}$$

Constraint (3.6) is the constraint of depot capacity that accounts for the total demands of ATMs assigned to a depot not to exceed the depot's capacity.

$$M z_{ij} \geq \sum_{f \in N} (x_{ifk} + x_{fjk}) \qquad \forall i \in I, \forall j \in J, \forall k \in K \tag{3.7}$$

Constraint (3.7) provides an ATM to be on the depot route to which the ATM is assigned.

$$\sum_{i \in N} x_{jik} \geq \beta_{jkp} \qquad \forall j \in J, \forall k \in K, \forall p \in P \tag{3.8}$$

Constraint (3.8) ensures that each ATM's demand can be met only if the vehicle goes through that location.

$$\sum_{k \in K} \beta_{jkp} = 1 \qquad \forall j \in J, \forall k \in K, \forall p \in P \tag{3.9}$$

Constraint (3.9) ensures that each ATM 's total demand can be met.

$$A_{jk} - L_{ik} + M(1 - x_{ijk}) \geq t_{ij} \qquad \forall i, j \in N, \forall k \in K \tag{3.10}$$

$$A_{jk} - L_{ik} + M(x_{ijk} - 1) \leq t_{ij} \qquad \forall i, j \in N, \forall k \in K \tag{3.11}$$

Constraint (3.10) and (3.11) add the departure time and travel time to determine the relevant node's arrival time.

$$A_{jk} + s_i + W_{ik} = L_{ik} \qquad \forall i \in J, \forall k \in K \tag{3.12}$$

Constraint (3.12) adds the waiting and service time passed at any node to the arrival time, allowing it to determine when it leaves the relevant node.

$$A_{ik} + W_{ik} \geq e_i \qquad \forall i \in N, \forall k \in K \tag{3.13}$$

$$L_{ik} \leq l_i \qquad \forall i \in N, \forall k \in K \tag{3.14}$$

Constraints (3.13) and (3.14) are time window constraints.

$$L_{1k} = 0 \qquad \forall k \in K \tag{3.15}$$

$$L_{2k} = 0 \qquad \forall k \in K \tag{3.16}$$

With constraints (3.15) and (3.16), the vehicle leaves the depots (node 1 and 2) at the start.

$$W_{qk} = 0 \qquad \forall q \in Q, \forall k \in K \tag{3.17}$$

With constraint (3.17), the vehicles cannot wait for the ATM with no parking area.

$$\sum_{i\in I}\sum_{j\in J} r_{ij}\, x_{jik} \leq R \qquad \forall k \in K \tag{3.18}$$

Constraint (3.18) ensures that the total risk cannot exceed the maximum risk for each vehicle.

$$U_{ik}, \beta_{jkp}, L_{ik}, A_{ik}, W_{ik} \geq 0 \qquad \forall i,j \in N, \forall k \in K, \forall p \in P \tag{3.19}$$

Constraint (3.19) is a non-negativity constraint for decision variables.

$$\sum_{k\in V}\sum_{i\in I}\sum_{j\in I} x_{ijk} = 0 \qquad \forall i,j \in I, \forall k \in K \tag{3.20}$$

Constraint (3.20) ensures that there are no routes to be travelled between any two depots.

$$x_{ijk,} z_{ij} \epsilon \{0,1\} \qquad \forall i,j \in N, \forall k \in K \tag{3.21}$$

Constraint (3.21) is a binary constraint for decision variables.

4. The Real Case Application in Istanbul

Within the scope of the study, the Beşiktaş district of Istanbul is considered as an application area for the CIT problem. The socio-economic population, location, shopping centers, schools, and business centers of the district play an important role in selecting the region. The process of money distribution to the ATMs of a public bank operating in this region is discussed. The bank has 19 ATMs and 2 depots in this region. All nodes can be

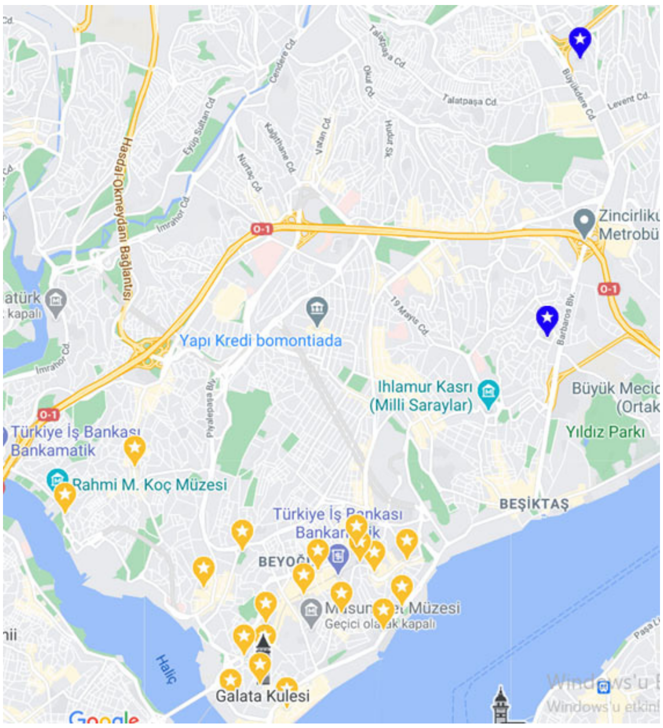

Figure 2: ATMs and depots at Beşiktaş region

seen in Figure 2. In the proposed methodology, the locations of the ATMs, the departure nodes and available parking areas are important. Google maps is used to determine the locations of these nodes. The distances between the ATMs are determined considering the actual travel/traffic distances.

Within the scope of this study, the CIT problem for 19 ATMs located in the Beşiktaş region in Istanbul is handled. Eight of these ATMs are located at bank branches, three in shopping centers, seven on the streets and one at the metro station. The locations of ATMs affect service times and time windows. For example, while the money loading service to ATMs should be completed before the shopping center is opened, for ATMs at bank branches, this service should be performed after the branch opening. Likewise, service times depend on ATM locations, too. For example, the service times of the ATMs at the metro stations are longer than the others. All the service times and time windows of the ATMs are determined according to historical data and expert opinions, and given in Table 2. The money distribution process starts at 06:00 and must finish before 14:00.

Table 2. Types, service times and time windows of ATMs

ATM ID	Service Time(min)	Earliest	Latest	ATM ID	Service Time(min)	Earliest	Latest
3	20	06:00	10:00	**13**	25	10:00	14:00
4	25	10:00	14:00	**14**	20	06:00	10:00
5	25	10:00	14:00	**15**	30	06:00	07:00
6	30	06:00	07:00	**16**	30	06:00	07:00
7	25	10:00	14:00	**17**	20	06:00	10:00
8	20	06:00	10:00	**18**	20	06:00	10:00
9	40	06:00	07:00	**19**	25	10:00	14:00
10	25	10:00	14:00	**20**	25	10:00	14:00
11	20	06:00	10:00	**21**	25	10:00	14:00
12	25	10:00	14:00				

Table 3. The demands of each ATM

ATM ID	Demand			ATM ID	Demand		
	€	$	₺		€	$	₺
3	10000	8000	150000	**13**	12000	15000	180000
4	10000	8000	170000	**14**	9000	12000	140000
5	20000	25000	240000	**15**	5000	6000	200000
6	5000	5000	200000	**16**	6000	5000	250000
7	14000	20000	220000	**17**	12000	10000	180000
8	4000	5000	140000	**18**	2500	10000	160000
9	22000	15000	300000	**19**	2000	2000	120000
10	9000	7000	130000	**20**	2000	2000	120000
11	5000	4000	150000	**21**	3000	3000	90000
12	15000	20000	280000				

The amount of money deposited to and withdrawn from the ATMs during the day is important for determining the daily money needs of the ATMs. Therefore, it is necessary to determine the daily money accurately. In this study, historical data is used to determine the amount of money required for each ATM. Table 3 gives the demand for each type of money for each ATM.

Armored vehicles are used to safely transport money from one destination to another. The cash needs of ATMs are met from the depot by armored vehicles. These vehicles have different types and different capacity constraints.

They have the same technical properties as each other; in other words, they are identical. The only difference is in terms of their insurance levels. The insurance level determines the maximum amount of money that a vehicle can carry; the higher the capacity of the vehicle, the more the cost of insurance. The firm has two different types of vehicles, two of each. The armored vehicles' capacities are given in Table 4.

Table 4. Vehicle capacities

Vehicle	Capacity		
	€	$	₺
1	47000	47000	1050000
2	47000	47000	1050000
3	42000	42000	700000
4	42000	42000	700000

The firm distributes money to ATMs from two different depots. These depots have different capacities for each money type. The capacities of depots are given in Table 5.

Table 5. Depot capacities

Depot	Capacity		
	€	$	₺
1	85750	90250	1800000
2	85750	90250	1800000

In this study, the CIT problem is studied. For the CIT problem, the risk factors are determined by a comprehensive literature review and then the most appropriate ones are specified by consulting with the anonymous experts that work on or study money transportation operations. As a result, the critical risk factors for money distribution are determined as the distance to residential areas, traffic density, the structure of the road, etc.

Road factors are important in determining risks for CIT operations. Traffic on the road, conditions of the road affect the accident risks that may cause theft. Road capacity can be determined according to the number of lanes in the road. The road material (gravel, asphalt, etc.) is taken into consideration in determining the risks. Also, deteriorated roads may cause an accident. So road condition plays an important role for money distribution. These factors are very important for possible accident and/or theft of the vehicle, which carries money from a depot to the ATMs. In this study, the risks of the roads the vehicle uses in the distribution network are determined by expert interviews. The experts determine the risk values of the roads between 0.1 and 0.9 considering the proximity of the road to shopping and residential areas, traffic density, the structure of the road, etc.

In this study, the Delphi technique is used when determining the risks. In the technique, interviews with five different experts were carried out face-to-face and via e-mail during the assessment of the risks. These experts work for money transportation operations. In addition, the opinions of two different academics taking part in academic studies and projects on similar subjects are also taken, and the first meeting is held with the experts and ideas were collected to better understand the current situation and the problem. These negotiations are repeated until consensus is achieved, and expert opinions are obtained again and again. At the end of the process, a comprehensive common opinion is shared with the experts about the risks. As a result of the evaluations expressed by the experts of the risks, it is concluded that the experts had same opinions about the risks. Thus, the identified risks are integrated into the study. Lastly, the maximum risk is set at 1.4 according to firm policy and consultation with experts to determine the optimum route.

After the values of all the parameters are determined, the optimum distribution routes obtained by the mathematical model are shown in Figure 3 with different colors for each vehicle. The mathematical model is solved by IBM ILOG Cplex OPL Optimization Studio 12.8.

The ATMs that each vehicle distributes according to their capacity, traveling times between ATMs, arrival times to ATMs, service and waiting times at ATMs and departure times from ATMs are given in Table 6.

The objective function for this route is determined as 87750 TL (Turkish Lira). According to obtained route, Vehicle 1 distributes money during the time period between 06:00-14:00. The vehicle departing from the depot follows the route of Depot 2-ATM 16-ATM 8-ATM 17-ATM 14-ATM 12-Depot 2. It arrives at ATM 16 at 06:12:00 and completes the money loading process at 06:42:00 including 30 minutes of service time, and departs from ATM 16. It arrives at ATM 8 at 06:47:00 and completes the money loading process at 07:07:00 including 20 minutes of service time; the vehicle waits for 2 hours and 3 minutes at ATM 8 and departs from ATM 8 at 09:10:00. It arrives at ATM 17 at 09:15:00 and completes the money loading process at 09:35:00 including 20 minutes service time and departs from ATM 17. It arrives at ATM 14 at 09:40:00 and completes the money loading process at 10:00:00 including 20 minutes of service time, and departs from ATM 14. Finally, Vehicle 1 arrives at ATM 12 at 10:03:00 and waits until 13:35:00 because of the earliest service time, then completes the money loading process at 14:00:00 including 25 minutes of service time and departs from ATM 12 and goes to Depot 2.

Vehicle 2 distributes money during the time period between 06:00-14:00. The vehicle departing from the depot follows the route of Depot 1-ATM 15-ATM 18-ATM 19-ATM

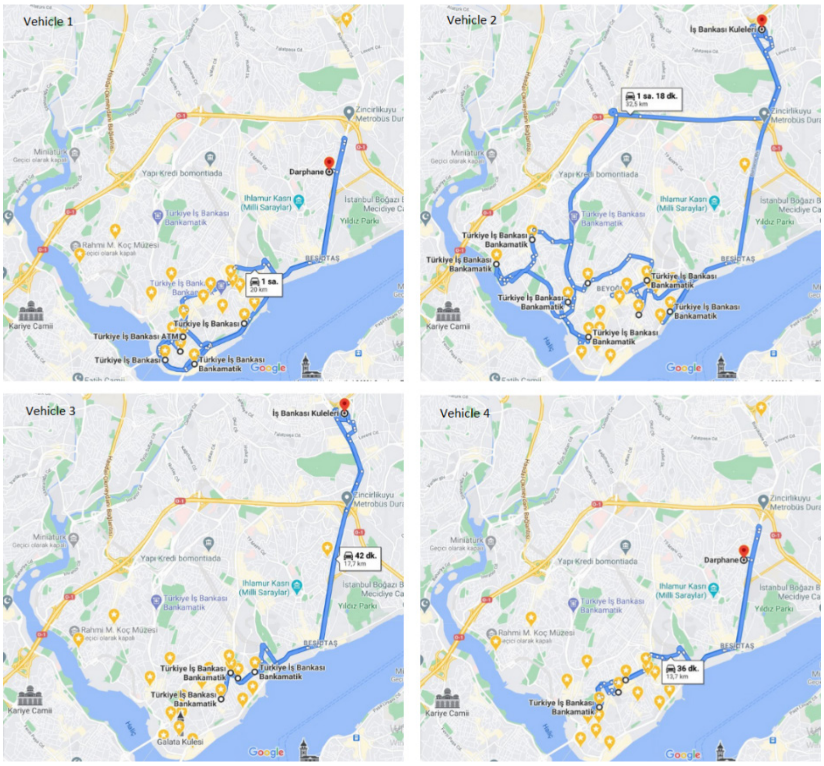

Figure 3: Optimum money distribution routes

7-ATM 10-ATM 5-Depot 1. It arrives at ATM 15 at 06:13:00 and completes the money loading process at 06:43:00 including 30 minutes service time and departs from ATM 9. It arrives at ATM 18 at 06:47:00 and completes the money loading process at 07:07:00 including 20 minutes of service time; the vehicle waits for 2 hours and 53 minutes at ATM 18 and departs from ATM 18 at 10:00:00. It arrives at ATM 19 at 10:04:00 and completes the money loading process at 10:29:00 including 25 minutes service time, and the vehicle waits for 2 hours and 4 minutes at ATM 19 and departs from ATM 19 at 12:33:00. It arrives at ATM 17 at 12:37:00 and completes the money loading process at 13:02:00 including 25 minutes of service time and departs from ATM 7. After that vehicle arrives at ATM 7 at 12:37:00 and completes the money loading process at 13:02:00 including 25 minutes of service time and departs from ATM 7. After that vehicle arrives at ATM 10 at 13:07:00 and completes the money loading process at 13:32:00 including 25 minutes service time and departs from ATM 10. Finally, vehicle 2 arrives at ATM 5 at 13:35:00 and completes the money loading process at 14:00:00 including 25 minutes of service time and departs from ATM 7 and goes to Depot 1.

Vehicle 3 distributes money during the time period between 06:00-14:00. The vehicle departing from the depot follows the route of Depot 2-ATM 9-ATM 8-ATM 13-ATM 21-ATM 20-Depot 2. It arrives at ATM 16 at 06:10:00 and completes the money loading process at 06:50:00 including 40 minutes of service time and departs from ATM 16. It arrives at ATM 8 at 06:52:00 and completes the money loading process at 07:12:00 including 20 minutes of service time; the vehicle waits for 2 hours and 48 minutes at ATM 8 and departs from ATM 8 at 10:00:00. It arrives at ATM 13 at 10:08:00 and completes the money loading process at 10:33:00 including 25 minutes of service time; the vehicle

Table 6. Money distribution route for each vehicle

Stop	Distance (km.)	Driving Time	Arrival Time	Service Time	Waiting Time	Departure Time
Vehicle 1						
Depot 2	-	-	-	-	-	06:00:00
ATM 16	6.2	00:12:00	06:12:00	00:30:00	-	06:42:00
ATM 8	1.9	00:05:00	06:47:00	00:20:00	02:03:00	09:10:00
ATM 17	1.8	00:05:00	09:15:00	00:20:00	-	09:35:00
ATM 14	1.1	00:05:00	09:40:00	00:20:00	-	10:00:00
ATM 12	0.8	00:03:00	10:03:00	00:25:00	03:32:00	14:00:00
Depot 2	6.6	00:11:00	14:11:00	-	-	-
Vehicle 2						
Depot 1	-	-	-	-	-	06:00:00
ATM 15	11.3	00:13:00	06:13:00	00:30:00	-	06:43:00
ATM 18	1.3	00:04:00	06:47:00	00:20:00	02:53:00	10:00:00
ATM 19	1.7	00:04:00	10:04:00	00:25:00	02:04:00	12:33:00
ATM 7	1.9	00:04:00	12:37:00	00:25:00	-	13:02:00
ATM 10	1.8	00:05:00	13:07:00	00:25:00	-	13:32:00
ATM 5	1.2	00:03:00	13:35:00	00:25:00	-	14:00:00
Depot 1	7.9	00:12:00	14:12:00	-	-	-
Vehicle 3						
Depot 2	-	-	-	-	-	06:00:00
ATM 9	5.3	00:10:00	06:10:00	00:40:00	-	06:50:00
ATM 8	0.75	00:02:00	06:52:00	00:20:00	02:48:00	10:00:00
ATM 13	2.5	00:08:00	10:08:00	00:25:00	02:25:00	12:58:00
ATM 21	3.2	00:07:00	13:05:00	00:25:00	-	13:30:00
ATM 20	1.8	00:05:00	13:35:00	00:25:00	-	14:00:00
Depot 2	6.6	00:10:00	14:10:00	-	-	-
Vehicle 4						
Depot 1	-	-	-	-	-	06:00:00
ATM 6	8.1	00:12:00	06:12:00	00:30:00	-	06:42:00
ATM 11	0.75	00:03:00	06:45:00	00:20:00	02:30:00	09:35:00
ATM 3	2.7	00:05:00	09:40:00	00:20:00	-	10:00:00
ATM 5	0.45	00:01:00	10:01:00	00:25:00	03:05:00	13:31:00
ATM 4	1.8	00:04:00	13:35:00	00:25:00	-	14:00:00
Depot 1	7.2	00:11:00	14:11:00	-	-	-

waits for 2 hours and 25 minutes at ATM 13 and departs from ATM 13 at 12:58:00. It arrives at ATM 21 at 13:05:00 and completes the money loading process at 13:30:00 including 25 minutes service time and departs from ATM 21. Finally, Vehicle 4 arrives at ATM 20 at 13:35:00 and completes the money loading process at 14:00:00 including 25 minutes of service time and departs from ATM 20 and goes to Depot 2.

Vehicle 4 distributes money during the time period between 06:00-14:00. The vehicle departing from the depot follows the route of Depot 1-ATM 6-ATM 11-ATM 3-ATM 5-ATM 4-Depot 1. It arrives at ATM 6 at 06:12:00 and completes the money loading process at 06:42:00 including 30 minutes of service time and departs from ATM 6. It arrives at ATM 11 at 06:45:00 and completes the money loading process at 07:05:00

including 20 minutes of service time; the vehicle waits for 2 hours and 30 minutes at ATM 11 and departs from ATM 11 at 09:35:00. It arrives at ATM 3 at 09:40:00 and completes the money loading process at 10:00:00 including 20 minutes of service time and departs from ATM 3. It arrives at ATM 5 at 10:01:00 and completes the money loading process at 10:26:00 including 25 minutes of service time; the vehicle waits for 3 hours and 5 minutes at ATM 5 and departs from ATM 5 at 13:31:00. Finally, it arrives at ATM 4 at 13:35:00 and completes the money loading process at 14:00:00 including 25 minutes of service time and departs from ATM 4 and goes to Depot 1.

4.1. Sensitivity Analysis

The proposed model for the CIT problem, which considers risks and different types of money for distribution, provides a more realistic approach than the mathematical models prepared for the traditional CIT problem. By solving the mathematical model, accurate and efficient results are obtained. The sensitivity analysis is performed to demonstrate and prove the proposed mathematical model's accuracy and efficiency by comparing

Table 7. Money distribution routes for each vehicle for Scenario 1

Stop	Distance (km.)	Driving Time	Arrival Time	Service Time	Waiting Time	Departure Time
Vehicle 1						
Depot 2	-	-	-	-	-	06:00:00
ATM 9	5.3	00:10:00	06:10:00	00:40:00	-	06:50:00
ATM 8	0.75	00:02:00	06:52:00	00:20:00	02:23:00	09:35:00
ATM 17	1.8	00:05:00	09:40:00	00:20:00	-	10:00:00
ATM 12	1.9	00:04:00	10:04:00	00:25:00	02:29:00	12:58:00
ATM 21	4.1	00:07:00	13:05:00	00:25:00	-	13:30:00
ATM 20	1.8	00:05:00	13:35:00	00:25:00	-	14:00:00
Depot 2	7.7	00:10:00	13:40:00	-	-	-
Vehicle 2						
Depot 1	-	-	-	-	-	06:00:00
ATM 15	11.3	00:13:00	06:13:00	00:30:00	-	06:43:00
ATM 18	1.3	00:04:00	06:47:00	00:20:00	02:53:00	10:00:00
ATM 19	1.7	00:04:00	10:04:00	00:25:00	02:04:00	12:33:00
ATM 7	1.9	00:04:00	12:37:00	00:25:00	-	13:02:00
ATM 10	1.8	00:05:00	13:07:00	00:25:00	-	13:32:00
ATM 5	1.2	00:03:00	13:35:00	00:25:00	-	14:00:00
Depot 1	7.9	00:12:00	14:12:00	-	-	-
Vehicle 3						
Depot 2	-	-	-	-	-	06:00:00
ATM 16	6.2	00:12:00	06:12:00	00:30:00	0	06:42:00
ATM 14	1	00:04:00	06:46:00	00:20:00	02:54:00	10:00:00
ATM 12	0.8	00:03:00	10:03:00	00:25:00	03:01:00	13:29:00
ATM 13	2	00:06:00	13:35:00	00:25:00	0	14:00:00
Depot 2	9.4	00:13:00	14:13:00			
Vehicle 4						
Depot 1	-	-	-	-	-	06:00:00
ATM 6	8.1	00:12:00	06:12:00	00:30:00	-	06:42:00
ATM 11	0.75	00:03:00	06:45:00	00:20:00	02:30:00	09:35:00
ATM 3	2.7	00:05:00	09:40:00	00:20:00	-	10:00:00
ATM 5	0.45	00:01:00	10:01:00	00:25:00	03:05:00	13:31:00
ATM 4	1.8	00:04:00	13:35:00	00:25:00	-	14:00:00
Depot 1	7.2	00:11:00	14:11:00	-	-	-

different risk levels. In the first scenario, the risk level is decreased to 1.3, and the problem is solved. Table 7 shows the results of the first scenario.

The objective function for this route is determined as 90850 TL in this scenario. Then, in the second scenario, the risk level is increased to 1.5, and the problem is solved. Table 8 shows the results of the second scenario.

Table 8. Money distribution routes for each vehicle for Scenario 2

Stop	Distance (km.)	Driving Time	Arrival Time	Service Time	Waiting Time	Departure Time
Vehicle 1						
Depot 2	-	-	-	-	-	06:00:00
ATM 9	5.3	00:10:00	06:10:00	00:40:00	0	06:50:00
ATM 8	0.75	00:02:00	06:52:00	00:20:00	01:58:00	09:10:00
ATM 17	1.8	00:05:00	09:15:00	00:20:00	0	09:35:00
ATM 14	1.1	00:05:00	09:40:00	00:20:00	0	10:00:00
ATM 12	0.8	00:03:00	10:03:00	00:25:00	03:32:00	14:00:00
Depot 2	6.6	00:11:00	14:11:00			
Vehicle 2						
Depot 1	-	-	-	-	-	06:00:00
ATM 15	11.3	00:13:00	06:13:00	00:30:00	-	06:43:00
ATM 18	1.3	00:04:00	06:47:00	00:20:00	02:53:00	10:00:00
ATM 19	1.7	00:04:00	10:04:00	00:25:00	02:04:00	12:33:00
ATM 7	1.9	00:04:00	12:37:00	00:25:00	-	13:02:00
ATM 10	1.8	00:05:00	13:07:00	00:25:00	-	13:32:00
ATM 5	1.2	00:03:00	13:35:00	00:25:00	-	14:00:00
Depot 1	7.9	00:12:00	14:12:00	-	-	14:12:00
Vehicle 3						
Depot 1	-	-	-	-	-	06:00:00
ATM 6	8.1	00:12:00	06:12:00	00:30:00	-	06:42:00
ATM 11	0.75	00:03:00	06:45:00	00:20:00	02:30:00	09:35:00
ATM 3	2.7	00:05:00	09:40:00	00:20:00	-	10:00:00
ATM 5	0.45	00:01:00	10:01:00	00:25:00	03:05:00	13:31:00
ATM 4	1.8	00:04:00	13:35:00	00:25:00	-	14:00:00
Depot 1	7.2	00:11:00	14:11:00	-	-	-
Vehicle 4						
Depot 2	-	-	-	-	-	06:00:00
ATM 16	6.2	00:12:00	06:12:00	00:30:00	-	06:42:00
ATM 12	1.8	00:05:00	06:47:00	00:25:00	05:15:00	12:27:00
ATM 13	2	00:06:00	12:33:00	00:25:00	-	12:58:00
ATM 21	3.2	00:07:00	13:05:00	00:25:00	-	13:30:00
ATM 20	1.8	00:05:00	13:35:00	00:25:00	-	14:00:00
Depot 2	7.7	00:10:00	14:10:00	-	-	-

The objective function for this route is determined as 87150 TL in this scenario. We see that our model gives the best result in scenario 2. The increase in the risk level constraints made the model work more conveniently. In the main problem, we used 1.4 as the risk level constraint; when we increase it like the second model in a sensitivity analysis, the vehicles work more freely and have the chance to choose the cheapest routes. Conversely, when we reduce the risk constraints as the first model of the sensitivity analysis, it costs more than before. As a result, if we choose the safest paths, the objective function will decrease.

5. Conclusion

This study aims to minimize the total distance with the given constraints of the model, including multi-depots, multi-products, split deliveries and time windows. Nineteen different ATM locations are taken, and Turkish liras (TL), Euros (€) and American dollars ($) are transported to nineteen ATMs from two different depots. The mathematical programming formulation is solved using IBM ILOG Cplex OPL Optimization Studio 12.8, routes of the vehicles are calculated, and the total distance is calculated as 87750 m. In addition, the model is examined for two different scenarios, which are increased risk and decreased risk constraints.

New vehicle routing problems that may arise in the future within the scope of merging cash machines of banks or after the positioning of new ATMs can be solved using this model. Also, the vehicle routing program in the model can be used not only for ATMs but also for the transportation of any risky product or any vehicle routing problem by removing the risk restriction. The proposed multi-product, multi-depot, time constraint, and split delivery mathematical model has been applied to real life application in Istanbul. The model can be further developed and used in larger areas. When the number of ATMs increases, the solution of the problem takes a long time, so this study and model can be developed and can be solved by increasing the numbers and variables with heuristic modeling.

The contributions of the paper to the literature and application area can be specified as follows: (1) To handle the CIT problem more realistically, a risk constrained multi-depot, multi-product, heterogeneous, fleet split delivery VRP with a time windows formulation is proposed; (2) A real application is presented to show the applicability and reliability of the methodology; (3) The mathematical model is run for different scenarios and the optimum routes obtained are compared; (4) It is aimed that the proposed method will be used for the purposes of improving the cash distribution strategies of organizations; (5) To the best of our knowledge, this study is the first real case proposing a multi-depot, multi-product, heterogeneous, fleet split delivery CIT problem with time windows.

In the real world, operational systems are always ATM specific. For this reason, our problem and proposed model have proven to be an interesting research topic with many possibilities for future research. The presented model considers the total travel distance. Other metrics such as environmental factors, the total distance and duration of congested segments, risk in the target region etc., could be incorporated into the model as a future direction. Conflicting objectives such as the environmental and economic objectives could be considered by developing multi-objective models. Bigger and/or combined regions can be selected as the application area for the CIT problem. Heuristic or metaheuristic algorithms can be developed to handle complexity. The problem can be modeled as stochastic or robust structures.

Peer Review: Externally peer-reviewed.
Conflict of Interest: Authors declared no conflict of interest.
Financial Disclosure: Authors declared no financial support.
Author Contributions: Conception/Design of Study- M.C.Ş., E.A., A.T.; Data Acquisition- M.C.Ş., E.A.; Data Analysis/ Interpretation- E.A., A.T.; Drafting Manuscript- M.C.Ş., E.A. Critical Revision of Manuscript- E.A., A.T.; Final Approval and Accountability- E.A., A.T.

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