

# A Multi-Objective Memetic Algorithm for Risk Minimizing Vehicle Routing Problem and Scheduling Problem

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## Abstract

In this paper, a new approach to risk minimizing vehicle routing and scheduling problem is presented. Forwarding agents or companies have two main concerns for the collection of high-risk commodities like cash or valuable commodities between the central depot and the customers: one; because of the high value of the commodities transported, the risk of ambush and robbery are very high. Two; the cost of a security guard that protects the vehicle is high. Therefore, the goals of these companies are to deliver and collect commodities with maximum security and minimum risk. Hence, in this paper, a multi-objective vehicle routing problem with time windows (VRPTW) is proposed to minimize risk and transportation costs. Finally, a memetic algorithm is designed to optimize the proposed model. The proposed algorithm is evaluated and compared with the non-dominated genetic algorithm (NSGAI) using Solomon VRPTW test sets. The results demonstrate that the presented approach is effective for valuables routing problem.

**Keywords:** Multi-objective vehicle routing problem with time windows, valuable commodities, risk minimization, Memetic algorithm.

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## 1. Introduction

Transportation is one of the important parts of the supply chain, which plays an essential role in reducing the costs of the organization. To reduce transportation costs, the vehicle routing problem (VRP) aims to optimize the distribution and collection of goods. The VRPs can be defined as the problems of designing delivery or collection routes between one or several depots and a number of customers, subject to some additional constraints depending on the real-life application. VRP has different variants such as VRP with time windows, open VRP, multi-depot VRP, green VRP, etc. Also, it is used in a variety of real problems. One of the applications of VRP is to optimize the transportation of valuable commodities between geographical scattered points. Although these related forwarding agents or companies use security equipment, armored vehicles, and security forces to increase the security of transportation, the use of these security approaches does not completely prevent armed robbery attacks. Therefore, proper planning is needed to increase transport security.

Two objectives of minimizing the risk and minimizing the costs are considered in the planning of transport routes of valuable commodities. Transportation risk is minimized by reducing valuable commodity losses, and costs are minimized by reducing the number of personnel required to carry (the employees include a driver and one or two security guards). Therefore, in this paper, a new approach based on vehicle routing problem with time windows (VRPTW) is designed to minimize risk and cost of high risk or valuable commodities transportation. Also, a new memetic algorithm is developed to optimize the proposed model.

The remaining parts of the paper are organized as follows. In section 2, the studies in this area are reviewed to identify key issues and research gaps. Section 3 describes the mathematical

formulation of the proposed VRPTW. The proposed memetic algorithm is presented in Section 4. Section 5 shows the numerical experiments and results. Finally, the conclusions and future works direction are given in section 6.

## 2. Literature Review

The studies of VRP under risk conditions are divided into two main categories of carrying hazardous materials (such as [Androutsopoulos and Zografos, 2012], [Pradhananga et al. 2014], [Bula et al. 2016], [Bula et al. 2017], [Chen et al. 2017], [Du et al. 2017], [Hu et al. 2017], [Rabbani et al. 2018], [Yuan et al. 2018], [Bula et al. 2019], and [Rabbani, Heidari and Yazdanparast, 2019]) and valuable commodities transportation. The studies of valuable commodities like cash or valuable goods are as follows.

One of the approaches used to increase the security of valuable commodities transportation in papers is the unpredictability of routes. [Ngueveu, Prins and Calvo, 2009], [Ngueveu, Prins and Calvo, 2010], [Yan, Wang and Wu, 2012], [Ngueveu, Prins and Calvo, 2013], [Michallet et al. 2014], [Talarico, Sörensen and Springael, 2015], and [Hooeboom and Dullaert 2019], [Yan, Wang and Wu, 2014], and [Constantino, Mourão and Pinto, 2017] used this approach to reduce risk. [Ngueveu, Prins and Calvo, 2009], [Ngueveu, Prins and Calvo, 2010], and [Ngueveu, Prins and Calvo, 2013] developed a new approach, called *m*-peripatetic, which prohibits the use of a link more than *m* times when each customer visits multiple times. [Yan, Wang and Wu, 2012] presented a study that uses a time-space technique to generate more flexible routes for carrying cash. [Yan, Wang and Wu, 2012] also used the time-space network flow technique to create non-similar solutions in the cash transportation model, with the difference that travel time was considered stochastic. Similarly, [Michallet et al. 2014] created non-

similar routes in different periods by changing the service sequences to customers. In this article, there is a particular emphasis on the element of time. The ordering of customers in a solution is changed by varying the arrival time to each customer in each period. [Talarico, Sörensen and Springael 2015] also minimized the risk of carrying cash by generating  $k$  dissimilar solutions. The authors presented a new index for calculating the similarity between the two solutions and generated non-similar solutions based on it. [Constantino, Mourão and Pinto, 2017] used arc routing problem for generating dissimilar solutions in consecutive days. [Hooeboom and Dullaert, 2019] generated unpredictable routes through changing the arrival time at each customer in successive periods. The authors modeled the variability of arrival times by VRP with multiple time windows. They also developed a new method called IGTS (Iterated Granular Tabu Search) to optimize the model.

Among the papers of VRP under risk conditions, [Talarico, Sörensen and Springael, 2015] and [Talarico et al. 2017] presented a new type of VRP called RCTVRP (Risk-constrained Cash-in-Transit Vehicle Routing Problem) that limits the amount of cash-in-transit risk according to the insurance coverage. [Talarico, Sörensen and Springael 2015] presented two metaheuristic structures for RCTVRP optimization that combine four algorithms to generate an initial solution and six local search algorithms to improve the solutions. Also, [Talarico et al. 2017] in other research developed a new metaheuristic algorithm named ACO-LNS (Ant Colony Optimization with Large Neighbourhood Search) to solve RCTVRP. Similarly, [Radojičić, Djeniđ and Maric, 2018] used RCTVRP to minimize the risk of carrying cash and developed a fuzzy GRASP (Greedy Randomized Adaptive Search Procedure) with path relinking to solve their model.

Moreover, [Talarico, Sörensen and Springael, 2015] presented a bi-objective decision model

that minimizes the risk of cash-in-transit and transportation costs. In this paper, in addition to the risk minimization function, the authors also used the risk constraint to control the maximum risk of each route. The model of this article has been optimized by PMOO-ILS (progressive multiobjective optimization with iterative local search). [Bozkaya, Salman and Telciler, 2017] proposed a bi-objective function to reduce the risk and cost of carrying valuable goods. They also calculated the composite risk by a weighted sum of two component risk of the usage frequency of the link and the socio-economic status of areas around the routes. [Xu et al. 2019] proposed a multi-commodities RCVRP. Given that each customer (bank branch, ATM, and supermarket) has different cash denominations, this paper presented an optimal mix of different cash denominations for distribution among customers. They also developed a hybrid tabu search to optimize their model.

Also, [Ghannadpour and Zandiyeh, 2019] presented a bi-objective VRP that minimizes the risk and costs of cash transport, and solved their model with a genetic algorithm. [Xu et al. 2019] developed a cash routing problem that minimizes the travel cost and the penalty cost of deviating from the expected demand of customers. [Radojičić, Marić and Takači, 2018] presented a fuzzy RCVRP with the objective of minimizing costs. They propose fuzzy numbers based on the risk threshold and the risk indexes of the routes to approximate their model to the real world. [Fallah-tafti, Vahdatzad and Sadeghieh, 2019] presented an integrated location, routing and inventory problem (LRIP) for cash carrying. Their proposed model includes two objectives of minimizing risk and cost.

It is essential in the planning and scheduling of a valuable commodity to maintain transport security and to use the least risky routes. Also, security guard costs are a part of the cost of valuable commodities transportation and reducing this cost while reducing risk can play

an effective role in optimizing the planning of transportation of valuable commodities. Therefore, providing an approach to reduce the risk of theft, along with reducing security guard costs, can help the valuables transport companies increase the security of collecting valuable commodities. This paper presents a multi-objective valuables commodity routing problem minimizing the risk of theft and fixed costs. A new memetic algorithm is also developed to optimize the proposed model, which is able to provide competitive solutions. The contributions of this paper are listed below.

- Providing a bi-objective model of minimizing risk and minimizing security guard costs
- Developing an efficient metaheuristic to optimize the proposed problem

### 3. Mathematical modeling

In this section, the bi-objective model of linear programming for risk minimizing VRPTW is presented. Objective functions include risk minimization and cost minimization. In this paper, the formula presented by [Talarico, Sørensen and Springael, 2015] is used to calculate the risk. The risk of transportation is measured by the probability of theft and the consequences of the event. The consequence of theft is equal to the amount of stolen commodity, and the probability of robbery in any link is considered to be equal to the distance because it isn't simply measurable and depends on the distance of each link. The cost function minimizes the personnel required for transportation to reduce costs. The number of staff is also decreased by reducing the number of vehicles. In other words, transportation costs are minimized by reducing the number of vehicles. In the following, indexes, parameters, and decision-making variables are introduced. (The number of customers is equal to  $N$ )

#### Indexes:

$i, j$  : Indexes of nodes (customers, banks, ATM, and etc.) and central depot of forwarder ( $i, j \in C$ )  
 $k$  : Index of vehicles ( $k \in K$ )

#### Parameters:

$d_{ij}$ : Travel distance between node  $i$  and node  $j$   
 $t_{ij}$  : Travel time between node  $i$  and node  $j$   
 $m_i$  : Demand of node  $i$   
 $f_i$  : Time needed to service node  $i$   
 $e_i$  : Earliest allowable service time for node  $i$   
 $l_i$  : Latest allowable service time for node  $i$   
 $q$  : Capacity of each vehicle  
 $r_k$  : Maximum allowed time of vehicle  $k$   
 $C_k$  : Fixed cost of using vehicle  $k$  (cost of personnel required)

#### Decision variables:

$x_{ijk}$  : 1, if vehicle  $k$  travels from node  $i$  to node  $j$ , otherwise 0.  
 $u_i$  : The aggregate load upon leaving node  $i$   
 $t_i$  : Arrival time at node  $i$   
 $w_i$  : Waiting time at node  $i$

The bi-objective non-linear programming model of risk minimizing vehicle routing problem with time windows is presented as follows.

$$f_1: \text{Min} \sum_{i=0}^N \sum_{\substack{j=0 \\ j \neq i}}^N \sum_{k=1}^K d_{ij} \times u_i \times x_{ijk} \quad (1)$$

$$f_2: \text{Min} \sum_{k=1}^K \sum_{j=0}^N C_k x_{0jk} \quad (2)$$

Subject to:

$$\sum_{k=1}^K \sum_{j=1}^N x_{ijk} \leq K \quad \forall i = 0 \quad (3)$$

$$\sum_{\substack{i=0 \\ i \neq j}}^N \sum_{k=1}^K (u_i + m_j) \times x_{ijk} = u_j \quad \forall j \in C \setminus \{0\} \quad (4)$$

$$\sum_{\substack{j=0 \\ j \neq i}}^N x_{ijk} = \sum_{\substack{j=0 \\ j \neq i}}^N x_{jik} \quad \forall i \in C, \forall k \in K \quad (5)$$

$$\sum_{\substack{j=0 \\ j \neq i}}^N x_{ijk} \leq 1 \quad \forall i \in C, \forall k \in K \quad (6)$$

$$\sum_{\substack{j=0 \\ j \neq i}}^N x_{jik} \leq 1 \quad \forall i \in C, \forall k \in K \quad (7)$$

$$\sum_{k=1}^K \sum_{\substack{i=0 \\ i \neq j}}^N x_{ijk} = 1 \quad \forall j \in C \setminus \{0\} \quad (8)$$

$$u_i \leq q \quad \forall i \in C \quad (9)$$

$$\begin{aligned} t_i + w_i + f_i + t_{i0} & \quad \forall i \in C \\ & - (1 - x_{i0k})M \leq r_k \quad \forall k \in K \end{aligned} \quad (10)$$

$$u_0 = 0 \quad (11)$$

$$t_0 = w_0 = f_0 = 0 \quad (12)$$

$$\begin{aligned} t_i + w_i + f_i + t_{i0} & \quad \forall i \in C \\ & - (1 - x_{i0k})M \leq t_j \quad \forall k \in K, \forall i \neq j \in C \end{aligned} \quad (13)$$

$$e_i \leq (t_i + w_i) \leq l_i \quad \forall i \in C \setminus \{0\} \quad (14)$$

$$x_{ijk} \in \{0,1\}, t_i \geq 0, \forall i, j \in C, \forall k \in K \quad (15)$$

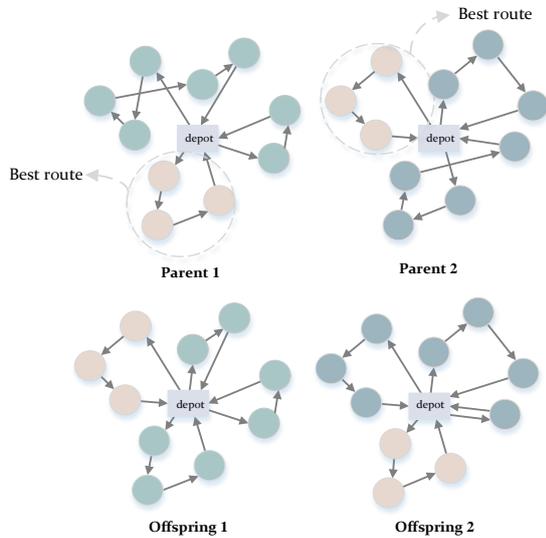
The equation (1) is the first objective function which minimizes the risk of robbery in transportation, and the equation (2) minimize the cost of personnel required to carry commodity. The equation (3) guarantees maximum  $K$  vehicles leave the central depot. The constraints (4) Indicates the aggregate vehicle's load upon leaving node  $i$ . The equations (5) - (8) ensure valuable commodities are collected exactly once by a vehicle. Also, Constraints (6) and (7) guarantee that each vehicle is not be used or departs from the depot once and return to it or is not be used. The constraint (9) is related to the capacity of the vehicle. The equation (10) ensures maximum travel time of each vehicle. The equation (11) and (12) guarantees the initial values of variables. The equations (13) and (14) apply the time windows constraints and calculates the arrival times.

#### 4. Solution Method

In this paper, the used solution algorithm to optimize the proposed model is the memetic algorithm. The memetic algorithm combines evolutionary algorithm and local search (see [Moscato, 1999] for further study of this algorithm). Also the evolutionary algorithms such as genetic algorithm have been used in other fields (see [Beheshtinia and Ghazivakili, 2018], [Beheshtinia, Ghasemi and Farokhnia, 2018], [Beheshtinia and Ghasemi, 2018], [Borumand and Beheshtinia, 2018], [Beheshtinia, Ahmadi and Fathi, 2019], [Najian and Beheshtinia, 2019], and [Taheri and Beheshtinia, 2019]). The proposed algorithm is as follows.

### 4.1 The Initial Population

The initial population is randomly formed. Each customer is assigned a number from one



**Figure 1. The crossover operation**  
to  $N$ , and then the numbers are randomly arranged. From the first customer, the first route is formed, and its adjacent customers are added to the route until the constraints of the problem are violated. Then the next route begins with the first unallocated customer, and this operation continues until all customers are allocated.

### 4.2 Crossover

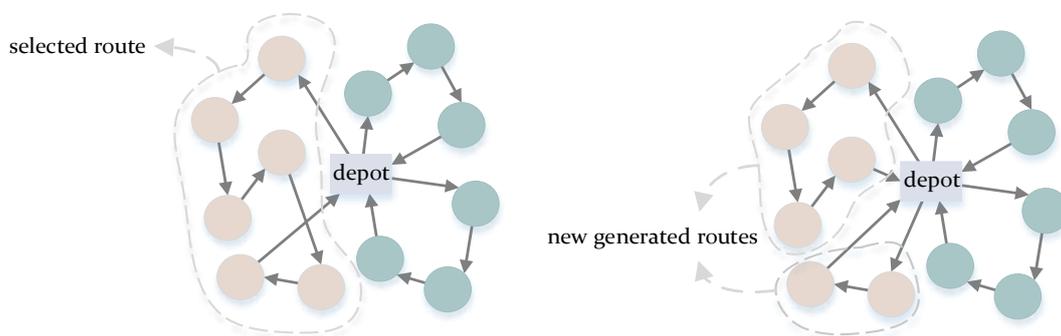
First, the parents are selected by the tournament selection (refer to [Tan et al. 2001] for more study), and then the parent crossover is done so that the best route (the one with the lowest proportion of cost to the number of customers) is selected from each parent and added to the other parent and customers on the best route from the opposite parent will be deleted [Bederina and Hifi, 2018]. The operation of this crossover is shown in Figure 1.

### 4.3 Mutation

The mutation operators try to maintain population diversity by changing some chromosome. The mutation algorithms of this paper include the following.

**Split route:** One of the routes that have more than three customers is randomly selected and split from a random point into two separate routes. Figure 2 displays an instance of this mutation.

**Merge routes:** Two routes are randomly selected and are combined into one single route, as shown in Figure 3.



**Figure 2. An example of split route**

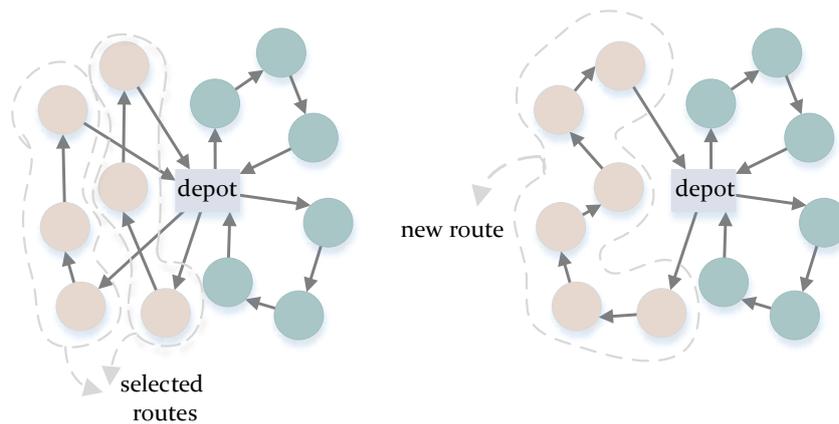


Figure 3. An example of merge routes

#### 4.4 Improvement

Local search is a strategy that improves the quality of the solution and, when combined with metaheuristic algorithms, has a very successful performance. Therefore, it is considered a complementary approach to evolutionary algorithms. Improvement algorithms of this paper include choosing one, two, or three customers from a route and assigning them to another route in a way that provides a lower-cost solution.

#### 4.5 Elitism

Elitism is a process that aims to retain the parents that remain non-dominated even concerning the newly generated offspring. Therefore, in evolutionary algorithms, the use of Elitism is necessary in order to converge the results [Rudolph and Agapie, 2000].

### 5. Computational Study

To examine the performance of proposed memetic algorithms, firstly, the parameters of the algorithm are tuned by Taguchi method. Then the results obtained by proposed algorithms are analyzed and compared with NSGAI presented by [Deb et al. 2002]. Along the way, two algorithms are compared based on the obtained final Pareto front.

#### 5.1 Parameter Setting

In this section, the procedures used to validate the efficiency of the memetic algorithm are presented. Before validating the solution method, the parameters of the algorithm must be set. [Taguchi and Wu, 1979] method is adopted to calibrate the parameters of proposed algorithms. To enhance the performance of the algorithm, the size of the parameters of

Table 1. Tuning values for various levels of the parameters

parameters	indicator	Level 1	Level 2	Level 3	Level 4	Optimal level
Population size	A	50	100	150	-	100
Crossover rate	B	0.2	0.4	0.6	0.8	0.6
Mutation rate	C	0.2	0.4	0.6	0.8	0.6
Improvement rate	D	0.2	0.4	0.6	0.8	0.8

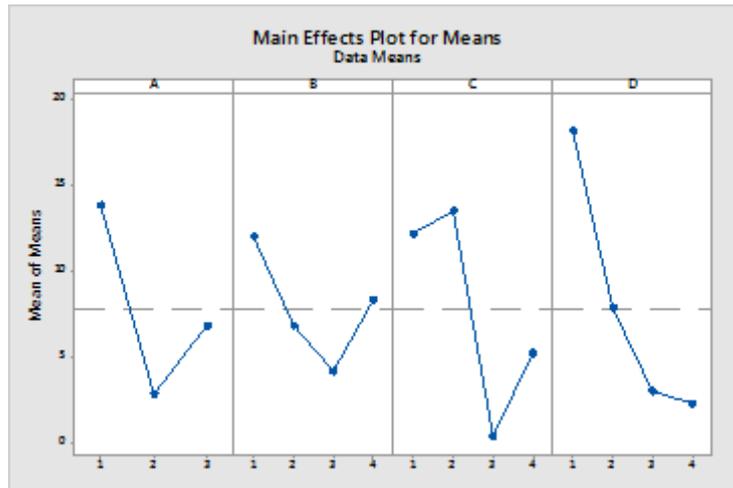


Figure 4. Experimental results of tuning four parameters based on Taguchi method

population size, crossover, mutation, and improvement are tuned by Taguchi method, and the value of other parameters of the algorithms is determined according to the literature. The levels of parameter values for the setting process are shown in Table 1. Also, Figure 4 shows the results of the experimentations.

The value of other parameters of the memetic algorithm derived from the work in [Ghoseiri and Ghannadpour, 2010] are as follows.

Generation number: 700.

Number of Elitism: 4.

### 5.2 Comparison of results

In this section, a number of [Solomon and Desrosiers, 1988] problems are randomly selected and solved by two algorithms, and two performance metrics are employed to analyze the effectiveness of proposed algorithms. The performance metrics are determined based on the obtained Pareto solution set for all the selected problems to evaluate the effectiveness of each algorithm, as reported in Table 2. The metrics include the minimum risk and the minimum cost obtained by the algorithms. It

Table 2. Comparison of memetic algorithm and NSGAI

Instance	NC	Memetic algorithm		NSGAI		Gap of BR %	Gap of BC %
		BR	BC	BR	BC		
C107	25	24002.9	30	30221.3	30	-20.58	0.0
R102	25	33175.5	70	39308	70	-15.60	0.0
RC204	25	44791.4	20	40131.3	20	11.61	0.0
C202	50	80749.5	30	134849.2	50	-40.12	-40
RC105	50	173635.8	90	196189.8	90	-11.50	0.0
R210	50	96833.0	50	121328.8	30	-20.18	25
C207	75	212181.6	50	257842.2	50	-17.71	0.0
R102	75	283218.9	160	321168.9	160	-11.82	0.0
RC104	75	287528.5	110	340276.4	100	-15.50	10
C109	100	460474.9	130	518310.0	110	-11.16	18.18
R107	100	390398.0	160	432813.8	130	-9.80	23.08
RC108	100	449691.4	160	627609.6	150	-28.35	6.67
Total						-17.1033	6.0

NC: Number of Customer, BR: Best Risk, BC: Best Cost, NPS: Number of Pareto Solution.

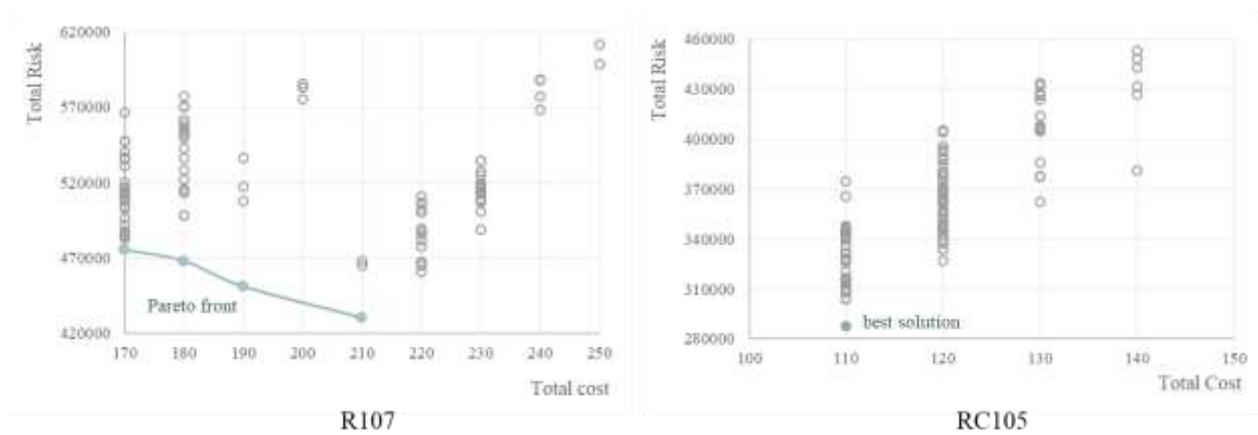


Figure 5. Solution set distribution and Pareto front of R107 and RC105

should be noted that the best cost and the best risk are not necessarily related to one solution (The cost of using any vehicle is considered 10).

As shown in Table 2, the proposed algorithm can keep good optimization performance in most of the instances. The results demonstrate that the memetic algorithm performs equally well for the objective of risk minimization, but NSGAI has better performance in the objective of cost minimization.

Before assessing the results, the relationship between risk and travel costs is unknown. Increasing the risk of an armed attack may increase travel cost, or the reduction of risk of theft could reduce the transportation costs of a solution. According to the Pareto front, the relationship between the two objectives can be achieved. The solutions obtained from the algorithm and the Pareto front of R107 and RC104 problems are shown in Figure 5.

As can be seen in Figure 1, in some problems, such as R107, there is a negative relationship between the robbery risk and the traveling costs (Multiplying the number of vehicles at a fixed cost of the security guards). The total traveling costs increased from 170 to 210, and the risk of a robber attack is reduced from 475260.7 to 390398.0. In some other problems, such as RC104, there is a positive relationship between the robbery risk and the traveling costs. By reducing the risk of an armed attack from

453107.5 to 287528.5, traveling costs are also reduced from 150 to 110. In this case, the Pareto front includes one problem.

## 6. Conclusions

In this paper, a two-objective VRPTW model was presented that could have a practical application in the collection of valuable commodities. The goals include minimizing the risk of armed robbery and transportation costs. The risk was calculated based on the amount of valuable commodities in the board of vehicles and the length of a link, and the traveling cost was considered equal to the fee of the required personnel (two security guards and one driver). A new memetic algorithm that combines a number of heuristic algorithms for crossover, mutation, and improvement is developed. Firstly, the parameters of the proposed algorithm were set by Taguchi method. Then it was examined by Solomon's problems, and the results were compared by two metrics with NSGAI algorithm, which results showed good performance of this algorithm.

This paper has presented an effective approach to the valuable commodities transportation so that in addition to minimizing the risk, the fixed cost of using the guard is minimized. Usually, as the number of vehicles increases, the risk of transport is reduced because it reduces the load on the vehicle, but the fixed costs increase,

which is not favorable for the transport company. The purpose of this paper is to find as safe as possible routes with the least theft probability so that increasing the load of the vehicle does not have a significant impact on the risk of theft. Finally, a route that minimizes both risk and cost is generated. So far, such a perspective has not been used to optimize the transportation of valuable commodities.

Future studies can include the unpredictability of the proposed model by reducing the similarity of the routes generated in successive periods. The proposed approach can also be used to transport cash, secret commodities, and hazardous material.

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