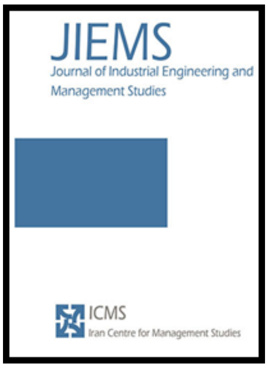
JIEMS

Journal of Industrial Engineering and Management Studies

Vol. 8, No. 1, 2021, pp. 202-217

DOI: 10.22116/jiems.2020.205786.1309

www.jiems.icms.ac.ir



Developing an environmental vehicle routing problem with simultaneous pickup and delivery: Mathematical model and a discrete invasive weed optimization approach

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Abstract

Nowadays, environmental deterioration is one of the most noticeable issues in logistics, so that the organizations are required to control the triggers of environmental contaminations generation. One of the most effective steps in addressing this term is to design transportation network considering CO_2 emission limitation. In this paper, a vehicle routing problem with simultaneous pickup and delivery with heterogeneous fleet and environmental measurement consideration is proposed. Introduced two objectives mathematical modeling, with the help of the weighted LP metric method has become to a combined dimensionless objective. The formulated optimization problem is solved in small dimensions using General Algebraic Modelling System (GAMS) approach and specifically BARON solver respect to the nature of the mathematical equations. The results obtained from simulations are discussed to confirm the effectiveness of the proposed method in dealing with the desired example. Because of NP-hardness, Discrete Invasive Weed Optimization (DIWO) meta-heuristic algorithm is applied.

Keywords: environmental vehicle routing problem; simultaneous pickup and delivery; weighted LP-metric; discrete invasive weed optimization.

Received: October 2019-19

Revised: January 2020-20

Accepted: January 2020-25

1. Introduction

The vehicle routing problem is an interesting logistics management problem. The wide range of the VRP variations from school bus problem and capacitated vehicle routing problem to the dispatching vehicles to pick up or drop off goods for customer by a variety of approaches is because of vital role of routing in logistics.

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The some basic vehicle routing problems are as following:

- The Traveling Salesman Problem
- The Chinese Postman Problem
- The M-Traveling Salesman Problem
- The Single Depot, Multiple Vehicle, Node Routing Problem
- The Multiple Depot, Multiple Vehicle, Node Routing Problem
- The Single Depot, Multiple Vehicle, Node Routing Problem with Stochastic Demands

Sometimes the logistics experts can improve vehicle utilization by performing pickups and deliveries jointly instead of using separate vehicles (G. Nagy et al. 2005). In the vehicle routing problem with simultaneous pickup and delivery, vehicles leave the depot and move towards customers and in each service, pick up kind of goods from any node and pick up another type of goods to the same node by the same vehicle. Practical example includes milk industry in which, vehicles pick up expired milk and picks up fresh ones to same customers at the same time.

Sustainable transport that is occasionally known as green transport as an agenda for addressing social, environmental and climate impacts is a vital subject in the logistics term. In the long run of the present transportation strategies unsustainability, the necessity for environmental logistics addressing is unavoidable. Hence in addition to the mainstream of economic calculations, environmental effects are taken into consideration when designing logistics policies.

The environmentally understanding logistic policy itself requires adapting the transportation plan onto a sustainable distribution network with fewer negative impacts on the environment and the ecology by promoting the alternative fuels, next generation electronic vehicles, green intelligent transportation systems and better utilization of vehicles, owing to the undeniable fact that transportation accounts for the major part of logistics (Lin C. et al. 2013).

In the realm of environmental approach, CO_2 is the primary greenhouse gas (GHG) emitted due to human activities like burning of fossil fuels in varied and multiple kinds of transportation. UN reported in 7 November 2016, according to the organization's annual report of its greenhouse gas emissions the United Nations emitted 1.9 million tons of carbon dioxide (CO_2) equivalent in 2016. Figure 1 demonstrates the united nations GHG emissions by source. The intergovernmental panel on climate change reports that transportation represents 14% of GHG emissions by economic sectors in 2010 (Pachauri et al. 2014).

It is inevitable to design an efficient logistics network with co2 emission control approach. In this research, in term of environmental measurement, the introduced method by Lee and Chen (2014) to measure carbon dioxide emitted by vehicles is applied. The process of measuring environmental term in the EVRPPD is based on the rate of co2 emission rate of each vehicle due to the consumption of fuel by vehicles. Lee et al. (2014) have considered fuel consumption rate for the full and empty load of each vehicles.

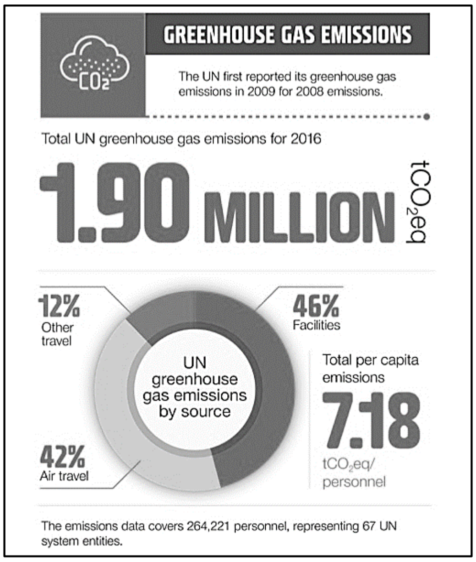

Figure 1. Total UN GHG emissions for 2016 (GREENING THE BLUE REPORT, 2017)

The purpose of this paper is to propose an environmental VRP with simultaneous pickup and delivery with single depot and heterogeneous fleet. Being NP-hard, to solve proposed problem meta-heuristic algorithm is applied. The intended algorithm is Discrete Invasive Weed Optimization (DIWO). During this research, weighted LP metric method is used to combine two objective functions.

The remainder of this research in organized as follows. In Section 2, we review the existing literature on vehicle routing problem with pickup and delivery, the extensions of the VRP with the green and environmental approach and the new approaches in related issues. Section 3 formulates the problem and mathematical modeling. Solution algorithm is presented in Section 4. Section 5 indicates computational results of the algorithm and the conclusion is presented in Section 6.

2. Literature review

2.1 Vehicle routing problem with pickup and delivery

Vehicle routing problem with pickup and delivery introduced by Dror et al. in 1989, and indicated the travel distance and number of vehicles can be reduced in case of split delivery. A lot of researches have been attended to solve VRPPD with heuristics algorithm and exact algorithm. A summary of the researchers' efforts to solve this type of problem by meta-heuristic algorithm is listed in table 1.

Table 1. A summary of solving VRPPD by meta-heuristic algorithm

	researcher	Algorithm	year
1	Dror et al.	local search algorithm	1989
2	Archetti et al.	tabu search algorithm	2006
3	Wilk et al.	genetic algorithm	2012
4	Archetti et al.	branch and cut algorithm	2014

Best of our knowledge, at the first time, vehicle routing problem with simultaneous pickup and delivery was proposed by Min et al. in 1989. The problem originated from books pickup and delivery between a central library and 22 branches. Much has been done to solve the problem by meta-heuristic algorithm, as shown in the table 2.

Table 2. A summary of efforts to solve VRPSPD by meta-heuristic algorithm

	Researchers	Algorithm	Year
1	Thangiah et al.	Genetic and local algorithm	1993
2	Chen and Wu	Hybrid heuristics	2006
3	Özyurt et al.	Art of VRPTD	2006
4	Zachariadis et al.	Particle swarm algorithm	2009
5	Subramanian et al.	Combination of VNP and iterated local search	2010
6	Tasan et al.	Ant algorithm	2012

2.2 The extensions of the VRP with the green and environmental approach

The Emissions Vehicle Routing problem (EVRP) with the purpose of the minimization of emissions and fuel consumption is the main objective of generalized cost function. Bektas and Laporte (2011) proposed the VRP intending environmental pollution has also been named Pollution routing problem (PRP). Xiao et al., (2012) introduced fuel consumption routing problem (FCVRP) and Erdogan and Miller-Hooks defined green vehicle routing problem in 2012.

K. Li et al. (2014) address a VRP with unpaired pickup and delivery with split delivery. In their proposed model, the supply point for each dropping off point is known earlier. Split delivery means a customer can be serviced by more than one vehicle. C.K.M. Lee et al. (2014) in their research introduced an environmental approach for VRPPD. It should be noted that in present paper we applied their method to measure co2 emission. They developed a hybrid artificial bee colony algorithm to solve the designed model.

A. Konak et al. (2016) with the purpose of minimizing GHG emission and improvement of planning of pickups and deliveries defined a green vehicle routing and scheduling problem with considering time-varying traffic congestion, heterogeneous fleet and time window for customers and vehicles. To solve their problem, they applied a hybrid algorithm mix integer programming and iterated neighborhood search. Taking into account the model solving approach, Kalayci et al. (2016) developed a hybrid meta-heuristic algorithm based on an ant colony system and a variable neighborhood search to solve VRPPD. Koç et al. (2016) extended the vehicle routing problem by considering a limited driving range of vehicles in conjunction with limited refueling infrastructure. They developed a simulated annealing heuristic based on branch-and-cut algorithm to solve the green vehicle routing problem, the exact algorithm for lower bound and meta-heuristic algorithm for upper bound.

Zhao et al. (2017) defined a Time-dependent vehicle routing problem with path flexibility (TDVRPPF) with considering saving cost and fuel consumption. Their proposed fuel consumption function is consisted of distance at a constant speed v in duration time t and carrying a load f. Consumption function F(v,t,f) includes coefficients like vehicle curb-weight, engine, speed and weight modules. Qi et al. (2017) proposed a modeling an inventory routing problem by environmental application (fuel consumption, carbon dioxide emission and load/distance/speed characteristics) with analyzing the advantages of using heterogeneous fleet with the purpose of minimizing overall cost. The MIP model is solved by Branch-and-Bound algorithm. M. Turkensteen et al. (2017) assume that the transport provider minimizes costs by use of a tool that calculates detailed vehicle routing plans, i.e., an assignment of each transport order to a specific vehicle in the fleet, and the sequence of customer visit for each vehicle. They also noticed the effect on carbon emissions of consolidation of shipments on trucks.

Onder Belgin et al. (2018) by considering the negative effects such as environmental pollution and traffic congestion proposed a two-echelon VRP with simultaneous pickup and delivery. In this logistics system, goods is dropped off to an intermediate depot and from that to customer. C. Rajendran et al. (2018) proposed a green VRPPD modeling for a semiconductor supply chain that named G-VRPPD-SSC. In this problem, goods are transported between nodes using AFVs. It means the vehicles that consume fuel sources are connected to as Alternative Fueling Stations (AFVs). H. Soleimani et al. (2018) propose a bi-objective non-linear programming model for the green vehicle routing problem (GVRP). Their model contains original and remanufactured products distribution of end of life (EOL) products including delivery and pickup. After applying fuzzy approach and linearizing they validated and solved the problem.

G. Poonthalir et al. (2018) extended the Green vehicle routing problem and introduced a bi-objective fuel efficient green vehicle routing problem with varying speed constraint by using goal programming and the purpose of minimizing route cost and fuel consumption. To solve this problem, they used PSO algorithm with Greedy Mutation. X. Wang et al. (2018) studied a low carbon for simultaneous pickup and delivery location routing problem with heterogeneous fleet. Their model includes time window constraint. To solve the proposed model, they introduced a two-phase hybrid algorithm including genetic algorithm for customer point clustering and variable neighborhood search algorithm for local search.

The table 3 indicates a summary of literature review for model with environmental approach. In next section, we descript a bi-objective MINLP model for EVRPSPD.

Table 3. Summary of literature for modeling with environmental considerations

	Authors	Year	Modeling approach
1	Bektas and Laporte	2011	Pollution routing problem
2	Xiao et al.	2012	Fuel consumption routing problem
3	Erdogan and Miller-Hooks	2012	Green vehicle routing problem
4	Gajanand and Narendran	2013	Green vehicle routing problem
5	C.K.M. Lee et al.	2014	Environmental vehicle routing problem
6	S. Madankumar et al.	2015	Green pickup and delivery problem in a semiconductor supply chain
7	A.Konak et al.	2016	The heterogeneous green vehicle routing and scheduling problem with time-varying traffic congestion
8	Ç. Koç et al.	2016	Green vehicle routing problem
9	C. cheng et al.	2017	Green inventory routing problem with heterogeneous fleet
10	M. Turkensteen et al.	2017	Combining pickups and deliveries in vehicle routing – An assessment of carbon emission effects
11	Poonthalir and Nadarajan	2018	A bi-objective Fuel efficient Green Vehicle Routing Problem
12	H. Soleimani et al.	2018	a vehicle routing problem with pickup and delivery considering sustainable and green criteria
13	X. Wang et al.	2018	Carbon reduction in the location routing problem with heterogeneous fleet, simultaneous pickup-delivery and time windows

Goli and Davoodi (2018) presented an optimization framework for producing and distribution in the supply chains with a cooperating strategy to achieve closed loop supply chain integration with open-shop manufacturing and economic lot and delivery scheduling problem (ELDSP). Given that the ELDSPR is an NP-hard problem, a simulated annealing (SA) algorithm and a biography-based optimization (BBO) algorithm is developed and two operational scenarios are formulated for the simulated annealing algorithm, after which both the algorithms are used to solve problems of different scales. Davoodi and Goli (2019)

developed an integrated model for relief operations in critical situations. The model is aimed at minimizing the late arrival of relief vehicles that cross points en route to disaster locations.
Goli et al. (2019) have proposed a hybrid improved artificial intelligence and robust optimization and a new method for calculating the risk of a product portfolio in the optimization of the product portfolio problem under return uncertainty. They applied an improved neural network with runner root algorithm (RRA) to predict the future demand of each product and calculating the risk index of each product based on its predicted future demand. To achieve this, Goli et al. (2019) proposed a two-objective (minimizing risk and maximizing return) mathematical model considering the effect of investments, reliability and allowable lost sales on the designed product portfolio. Goli et al. (2019) in another research addressed a novel robust Flow Shop Scheduling (FSS) problem with outsourcing option where jobs can be either scheduled for inside or outsourced to one of the available subcontractors. Capacity limitation for inside resource, just-in-time delivery policy and uncertain processing time are the key assumptions of the proposed model.
Because of constant development of gas utilization in domestic households, industry, and power plants transform to gaseous petrol into a noteworthy wellspring of energy and requisition of a great attention from the management of the supply chain to provide a significant development of gas trading to supply and transportation planning of liquefied natural gas (LNG), Sangaiah er al. (2019) have addressed a robust mixed-integer linear programming model for LNG sales planning over a given time horizon aiming to minimize the costs of the vendor. A cuckoo optimization algorithm (COA) is designed to solve the problem efficiently.

2.3 Developed invasive weed optimization algorithm

Many studies were carried out with inspirations from ecological phenomena for developing optimization techniques. IWO algorithm is a novel numerical stochastic optimization algorithm inspired from colonizing weeds which proposed by Mehrabian and Lucas in 2006. Successful results from diverse applications of this algorithm indicate the feasibility, the efficiency and the effectiveness of IWO.

In the realm of this IWO algorithm, Babaee Tirkolaee et al. (2019) have addressed a novel robust bi-objective multi-trip periodic capacitated arc routing problem under demand uncertainty to treat the urban waste collection problem and IWO is developed to solve the proposed model. They have mentioned that Multi Objective Invasive Weed Optimization is regarded as the best method to solve the large-sized multi-trip periodic capacitated arc routing problem. Goli et al. (2019) have found that the implementation of the robust optimization approach and IWO algorithm considering the profit margin uncertainty in real-world investment decisions is the research gap in the Product portfolio optimization field.

Goli et al. (2019) proposed the multi-objective, multi-products and multi-period closed-loop supply chain network design with uncertain parameters, whose aim is to incorporate the financial flow as the cash flow and debts' constraints and labor employment under fuzzy uncertainty. The objectives of the proposed mathematical model are to maximize the increase in cash flow, maximize the total created jobs in the supply chain, and maximize the reliability of consumed raw materials. To encounter the fuzzy uncertainty in this model, a possibilistic programming approach has used. To solve large-sized problems, the multi-objective simulated annealing algorithm, multi-objective gray wolf optimization, and multi-objective invasive weed optimization are proposed and developed.

In the next section, a vehicle routing problem with simultaneous pickup and delivery with heterogeneous fleet and environmental measurement consideration is proposed. Introduced two objectives mathematical modeling, with the help of the weighted LP metric method has become to a combined dimensionless objective. The formulated optimization problem is solved in small dimensions using General Algebraic Modelling System (GAMS) approach and specifically BARON solver respect to the nature of the mathematical equations. The results obtained from simulations are discussed to confirm the effectiveness of the proposed method in dealing with the desired example. Because of NP-hardness, Discrete Invasive Weed Optimization (DIWO) meta-heuristic algorithm is applied.

3. Mathematical modeling

In this research, single depot denoted by 0 (the first node) and heterogeneous fleet of vehicles are assumed, which means all of vehicles with different specifics like capacity or rate of carbon dioxide emission, depart from and turn back to the depot. Let G = (N, A) be an undirected graph in which N is the set of nodes and A represents the set of arcs that defines as A= {(i,j) : i,j ∈ N, i≠j}. The objectives functions include minimization of total distance traveled by fleet and co_2 emission for each vehicle. Finally, finding the optimal routing solution for pickup and delivery of goods is aimed. For the convenience of the reader, we provide table 4 listing the notations and the EVRPSPD is formulated as a mix integer non-linear program (MINLP).

Table 4. Notation used for EVRPSPD

Indices and sets	N	Set of the nodes
	C	Set of the customers
	O	Index of depot
	i,j	Indices of the nodes
	k	Index of vehicle
	K	Set of the vehicles
Parameters	d_{ij}	Length of arc_{ij}
	Dem_i	Demand for node i of the deliverable goods
	$Pick_i$	Demand for node i of the pickup goods
	Cap_k	Capacity of vehicle k
	roe_k	The fuel consumption rate for empty load vehicle
	rol_k	The fuel consumption rate for full load vehicle
	cer_k	The co_2 emission rate
	W	Weight related to LP metric method
Variables	X_{ijk}	A binary decision variable representing a dispatch decision, 1 if and only if truck k traverses arc_{ij}, and 0 otherwise.
	L_{ik}	An integer variable indicating the load of vehicle k from deliverable goods on node i.
	P_{ik}	An integer variable indicating the load of vehicle k from pickup products on node i.
	q_{ijk}	The load of vehicle k on arc_{ij}

$$\min \sum_{i\in N} \sum_{\substack{j\in N;\\ i\neq j}} \sum_{k\in K} d_{ij} x_{ijk} \tag{1}$$

$$\min \sum_{i\in N} \sum_{\substack{j\in N;\\ i\neq j}} \sum_{k\in K} cer_k \frac{rol_k - roe_k}{cap_k} q_{ijk} d_{ij} x_{ijk} \tag{2}$$

$$\sum_{\substack{i\in N;\\ i\neq j}}\sum_{k\in K} x_{ijk} = 1 \quad \forall j \tag{3}$$

$$\sum_{\substack{i\in N;\\ i\neq j}} x_{ijk} = \sum_{\substack{i\in N;\\ i\neq j}} x_{jik} \quad \forall j \text{ and } k \tag{4}$$

$$\sum_{j\in C} x_{ijk} \leq 1 \quad i = o \text{ and } \forall k \tag{5}$$

$$L_{ik} + P_{ik} \leq Cap_k \quad \forall i \in N\ k \in K \tag{6}$$

$$L_{ik} - Dem_i - M(1 - x_{ijk}) \leq L_{jk} \quad \forall i.j \in N; i \neq o \text{ and } i \neq j.k \in K \tag{7}$$

$$L_{ik} - Dem_i + M(1 - x_{ijk}) \geq L_{jk} \quad \forall i.j \in N; i \neq o \text{ and } i \neq j.k \in K \tag{8}$$

$$P_{ik} - Pick_i - M(1 - x_{ijk}) \leq P_{jk} \quad \forall i.j \in N; i \neq o \text{ and } i \neq j.k \in K \tag{9}$$

$$P_{ik} - Pick_i + M(1 - x_{ijk}) \geq P_{jk} \quad \forall i.j \in N; i \neq o \text{ and } i \neq j.k \in K \tag{10}$$

$$L_{jk} + P_{jk} \leq M \sum_{\substack{i\in N;\\ i\neq j}} x_{ijk} \quad \forall j \in N.k \in K \tag{11}$$

$$L_{ik} + P_{ik} = q_{ijk} \quad \forall i \in N\ k \in K \tag{12}$$

$$x_{ijk} = binary \quad \forall i.j.k \tag{13}$$

$$q_{ijk} \geq 0 \quad \forall i.j.k \tag{14}$$

$$L_{ik} \geq 0 \quad \forall i.k \tag{15}$$

$$P_{ik} \geq 0 \quad \forall i.k \tag{16}$$

The objective function (1) represents the total distance traveled by the heterogeneous fleet and the objective function (2) is designed to measure the CO_2 emission. The objective function (2) is proposed by Zhang et al. (2014). It expresses the consumption of certain type of fuel for vehicles as the cause of the emission of CO_2. The CO_2 emission rate is relative fixed provided that the type of fuel is known. The fuel consumption rate is determined by the traveling distance and the load of vehicles.

Constraint (3) ensures each customer is serviced by only one vehicle. Equation (4) is a flow conservation constraint. Constraint (5) guarantees each vehicle dispatches from and turns back to depot. Constraint (6) indicates the capacity of each vehicle's capacity is checked before entering any node. Constraints (7) and (8) define as follow: node i has demand Dem_i and vehicle k has L_i goods for delivering, accordingly, vehicle k ought to contain L_{ik}-Dem_i goods ready to deliver before arriving node j. For Constraints (9) and (10), node i has $Pick_i$ goods for giving back, thus, vehicle k ought to have capacity to pick up P_{ik}+$Pick_i$ before arriving node j. Constraint (12) ensures the variables L_{jk} and P_{jk} can get the amounts when

vehicle k would arrive node j. Constraints (13), (14), (15) and (16) define the decision variables.
For as much as, both of objectives (1) and (2) is minimized, by using the weighted LP metric method for bi-objective model with small-size and medium-size before application of meta-heuristic algorithm, objectives (1) and (2) is combined as follow formula:

$$\min obj = W \frac{obj_1^* - obj_1}{obj_1^*} + (1 - W) \frac{obj_2^* - obj_2}{obj_2^*} \tag{17}$$

In order to test the performance of the problem proposed before, we developed a reckoning example in small-size. The problem is coded in GAMS 25.0.2 and executed on a desktop computer with the Intel® Core™ i3-3110M CPU@ 2.40GHz. Being non-linear, the proposed two-objective function after applying LP metric method to make objective functions combined and dimensionless, is solved by GAMS@ code and BARON solver (results in table 5). Computational results show that the problem with small and medium size and by a powerful solver such as BARON can be solved optimally within acceptable computation time. For large-size problem because of NP-hardness and due to IWO algorithm wide range applicability and relative fast convergence rate, we are applied this meta-heuristic algorithm.

Table 5. The routes for vehicles

obj1	obj2	w	1-w
2354	2.9975629	0.2	0.8
2276	7.038509	0.4	0.6
2276	7.038509	0.6	0.4
2329	5.9444131	0.8	0.2
2329	5.9444131	1	0

We have formulated a mixed integer non-linear programming (MINLP) model for the problem, and use the MINLP solver BARON of the optimization suite GAMS 25.0.2 to solve it for 10 nodes in 130 minutes. According to LP metric method, we define the third objective to cover equation (17). The parameter w is 0.8, after 11 iterations with increment equal 0.1. By this approach, the tours for the vehicles 1, 2, 3 and 4 are as following table 6 and figure 2. In each node, we indicated amount of variables L_{ik} and P_{ik}.

Table 6. The routes for vehicles

vehicles	Capacity	cer	roe	rol	route
Truck 1	102	2.61	0.296	0.390	1-2-6-1
Truck 2	110	2.61	0.296	0.390	1-4-9-3-1
Truck 3	103	2.61	0.296	0.390	1-7-5-8-10-1
Truck 4	118	2.61	0.296	0.390	1

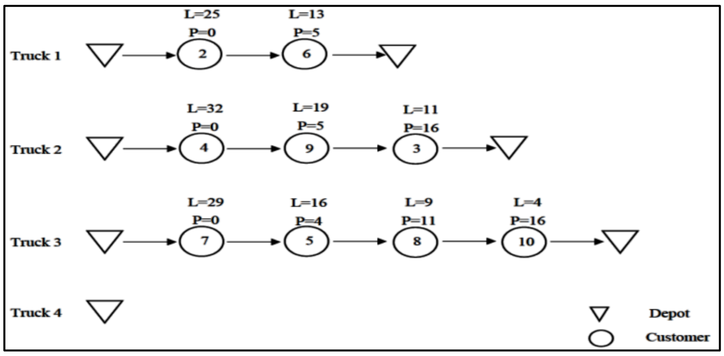

Figure 2. Routes resulting from GAMS approach

From figure 2, it is noticed that the circles indicate the customers and triangles show depot. The numbers in the circles are the node number and the numbers over the circles are the product quantity for the load of each truck from deliverable goods on nodes (L) and the load of each truck from pickup products on node (L).

4. Discrete invasive weed optimization algorithm

In the real world, EVRPSPD can be assumed as a NP-hard problem. The complexity of this problem is because of increasing the number of the nodes. To solve large scale problem, exact method can be hard and time-consuming. To achieve attractive result, it is inevitable to apply meta-heuristic algorithm. This paper proposed a meta-heuristic approach based on Discrete Invasive Weed Optimization (DIWO) algorithm to solve the EVRPSPD.

The IWO algorithm is developed by Mehrabian and Lucas in 2006. This algorithm is inspired from colonization of invasive weed. In initialization step, a population of seeds (initial solutions) is produced randomly over the search area. Reproduction is done by fitness of plants calculating based on following figure 3. As it's illustrated, the number of seeds each plant produce raises from minimum possible seed production to its maximum linearly and a plant will produce seeds based on its fitness. The colony's lowest fitness and highest fitness make sure the linear increasing.

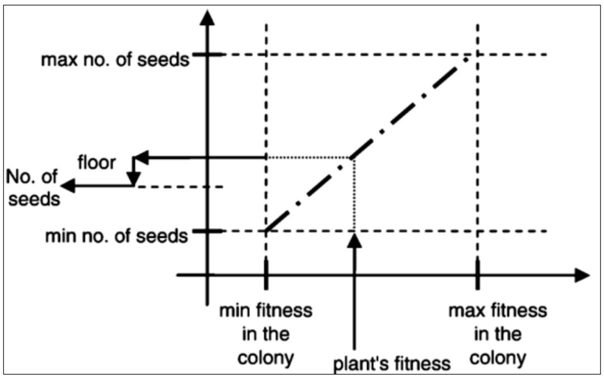

Figure 3. Reproduction procedure based on plants' fitness (Mehrabian and Lucas, 2006)

The number of seeds produced by each plant is calculated by following formulation:

$$S = \left\lfloor S_{min} + (S_{max} - S_{min})\ \frac{F - F_{worst}}{F_{best} - F_{worst}} \right\rfloor \quad (18)$$

Spatial dispersal guaranteed the generated seeds (initial solutions) are being randomly scattered over the search space (the parent plant) and grow to new plants (local search). Seeds spread according to a normal distribution. According to IWO process and based on r/K selection theory, we want to move from r-selection as an exploration step (quantitative) to K-selection as an exploitation approach (qualitative). Hence, the standard deviation of the seeds decrease (figure 4) as a function of the number of iterations, calculating by following equation in which n is the nonlinear modulation index:

$$\sigma_{iter} = \frac{(iter_{max} - iter)^n}{(iter_{max})^n}\left(\sigma_{initial} - \sigma_{final}\right) + \sigma_{final} \quad (19)$$

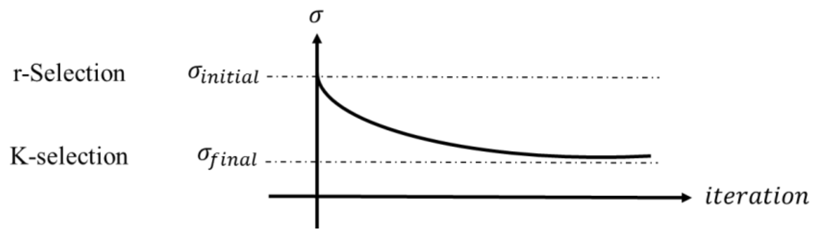

Figure 4. The standard deviation decreasing process

After passing some iterations, in the competitive exclusion step, the number of weeds will reach its maximum by fast reproduction, however, it is expected that the fitter weeds have been reproduced more than undesirable weeds, by reaching the maximum number of plants, for removing the plants with low fitness in the generation activates a process continues. The pseudo code for Discrete IWO algorithm is shown in figure 5:

1. Generate random population fitness in the colony feasible solutions
2. i=1
3. do
   a. compute the maximum and minimum fitness in the colony
   b. for each individual w∈W
      i. compute the number of seeds for w corresponding to its fitness
      ii. randomly select the seeds from the feasible solutions around the parent plant (w) in the neighborhood with normal distribution
      iii. add the generated seeds to solution set W
   c. if [W]=N>P_{max}
      i. sort the population N in descending order of their fitness
      ii. truncate population of weeds with smaller fitness until N= P_{max}
   d. i=i+1
4. repeat 3 until the maximum number of iterations

Figure 5. Pseudo code for Discrete IWO algorithm

The parameters of Discrete IWO for introduced model (as shown in table 7) are tested by signal to noise ratio analysis test introduced by Taguchi et al. (2005). After implementing the needed experiments for proposed meta-heuristic algorithm by Taguchi method, the S/N ratio is calculated, and the appropriate value for each parameter is specified based on the minimum S/N value.

Table 7. Parameters of Discrete IWO for EVRPSPD

Parameters	Definition	Tested value			selected value
nPop0	Number of initial seeds	6	6	10	10
MaxIt	Maximum number of iterations	20	80	200	200
Dim	Dimension of problem	18	20	22	18
P_{max}	Maximum number of weeds	15	20	25	25
S_{max}	Maximum number of seeds	3	4	5	5
S_{min}	Minimum number of seeds	0	1	2	0
$Sig_{initial}$	Initial value of standard deviation	0.25	0.5	0.75	0.25
Sig_{final}	final value of standard deviation	1.0*e-05	1.0*e-04	1.0*e-03	1.0*e-05
N	Non-linear modulation index	1	2	3	1

It is vital to mention, despite spatial dispersal stage, DIWO's framework is close to IWO's in initialization, reproduction and competition. DIWO is the adapted form of IWO for discrete optimization problem with efficient optimal solutions gaining for small and medium scaled problem. Compared to IWO, spatial dispersal is a random selection of solution from a neighbouring hypercube with a normal distribution in the discrete space of solution (Ramezani Ghalenoei et al. 2009).

5. Computational result

This section represents the result of computational result on DIWO algorithm approach for EVRPSPD problem. We consider a matrix for 22 nodes in which each element shows the distance between each couple nodes. The proposed model is tested using MATLAB R2017b. As an applied example, we solved EVRPSPD by DIWO algorithm in accordance with intended distance matrix (table 8). We set the parameters cer, roe and rol based on practical case study by Ubeda et al. (2011) and other inputs are taken randomly. The results of solving with meta-heuristic approach are demonstrated in figure 6 which shows the variation of objective function by iterations increasing and figure 7 that indicates allowed tours for proposed example.

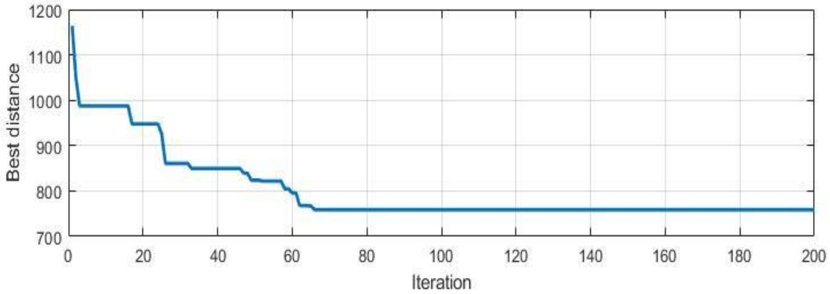

Figure 6. Objective value vs. iterations

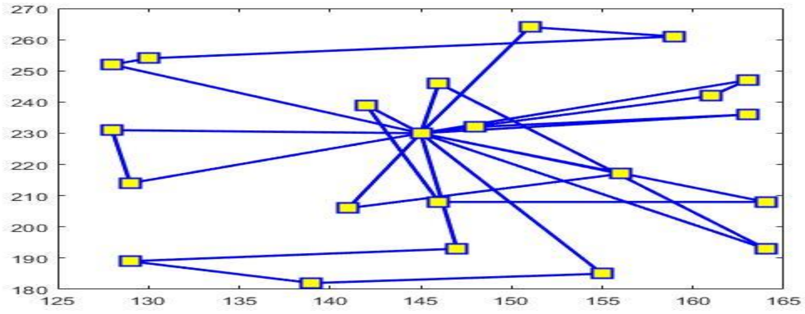

Figure 7. Network construction for the example based on table 7 and table 8

Table 8. Distance matrix example for proposed EVRPSPD

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	0	40	45	39	39	35	17	28	12	24	5	18	24	32	23	41	28	39	56	57	55	54
2	40	0	11	31	35	29	23	32	34	40	35	56	52	72	61	69	68	75	84	97	83	94
3	45	11	0	36	40	18	28	21	39	29	40	61	47	77	66	58	73	80	73	102	80	99
4	39	31	36	0	4	40	24	43	27	51	40	25	63	41	62	80	59	78	95	66	94	81
5	39	35	40	4	0	40	24	43	27	51	40	21	63	39	62	80	59	78	95	64	94	81
6	35	29	18	40	40	0	18	7	29	11	30	51	37	67	56	40	63	70	55	92	70	89
7	17	23	28	24	24	18	0	19	11	27	16	33	39	49	38	56	45	54	71	74	70	71
8	28	32	21	43	43	7	19	0	22	8	23	44	30	60	49	37	56	63	52	85	63	82
9	12	34	39	27	27	29	11	22	0	24	13	22	36	38	35	53	34	51	68	63	67	60
10	24	40	29	51	51	11	27	8	24	0	19	40	26	56	45	29	52	59	44	81	59	78
11	5	35	40	40	40	30	16	23	13	19	0	21	23	37	26	40	33	40	55	62	54	59
12	18	56	61	25	21	51	33	44	22	40	21	0	42	18	41	59	38	57	74	43	73	60
13	24	52	47	63	63	37	39	30	36	26	23	42	0	30	19	17	26	33	32	55	33	52
14	32	72	77	41	39	67	49	60	38	56	37	18	30	0	23	41	20	39	56	25	55	42
15	23	61	66	62	62	56	38	49	35	45	26	41	19	23	0	18	7	16	33	36	32	33
16	41	69	58	80	80	40	56	37	53	29	40	59	17	41	18	0	25	32	15	54	32	51
17	28	68	73	59	59	63	45	56	34	52	33	38	26	20	7	25	0	19	36	29	35	26
18	39	75	80	78	78	70	54	63	51	59	40	57	33	39	16	32	19	0	17	22	16	19
19	56	84	73	95	95	55	71	52	68	44	55	74	32	56	33	15	36	17	0	39	17	36
20	57	97	102	66	64	92	74	85	63	81	62	43	55	25	36	54	29	22	39	0	30	17
21	55	83	80	94	94	70	70	63	67	59	54	73	33	55	32	32	35	16	17	30	0	19
22	54	94	99	81	81	89	71	82	60	78	59	60	52	42	33	51	26	19	36	17	19	0

It is apparent that the proposed DIWO can obtain the feasible solution close to optimal solution. The proposed method and the computational results indicate the computing time is significantly reduced by applying meta-heuristic method proposed in this paper. In compare to meta-heuristic algorithm, using GAMS approach to solve EVRPSPD, because of NP-hardness and iterations for finding appropriate weights in LP metric method takes a longer time. Nevertheless, it is found that the BARON solver and its sub-solver is a powerful approach to solve this kind of problem in small and medium size.

6. Conclusion

In this paper, we proposed an environmental vehicle routing problem with simultaneous pickup and delivery for heterogeneous vehicles. By environmental approach, we measure the co_2 emissions by the vehicles with different rate of fuel consumption in full-load and empty-load conditions. A mathematical model of nodes, paths, trucks and depot is developed using a matrix approach and the objective functions and constraint equations are generated in detail. Before investigating performance of discrete invasive weed optimization algorithm to solve the problem, because of being two-objective, we used weighted LP metric technique to combine objective functions and make them dimensionless. For as much as one of the objective functions is non-linear and being mix integer non-linear programming, to deal with the optimization problem by General Algebraic Modelling System (GAMS) approach in small and medium size, we used a powerful solver such as BARON. The obtained results show the effectiveness of the used method in finding the optimal tours for each truck. DIWO as a numerical stochastic search algorithm is applied as a metaheuristic approach for large scale problem. The results show that the proposed DIWO can be obtained acceptable solutions for the in-hand problem. It is necessary to study as much as possible to prove the ability of DIWO to solve the other kinds of routing problem.

Reference

Archetti, C., Speranza, and M. G., Hertz, M., (2006). "A tabu search algorithm for the split delivery vehicle routing problem", *Transportation Science*, Vol. 40, No. 1, pp. 64-73.

Babaee Tirkolaei, E., Goli, A., and Malekalipour Kordestanizadeh, R., (2019). "A robust bi-objective multi-trip periodic capacitated arc routing problem for urban waste collection using a multi-objective invasive weed optimization", *Waste Management & Research*, pp. 1-13.

Bektas, I. and Laporte, G., (2011). "The Pollution-Routing Problem", *Transportation Research Part B: Methodological*, Vol. 45, No. 8, pp. 1232-1250.

Belgin, O., Karaoglan, I., and Altiparmak, F., (2018). "Two-echelon vehicle routing problem with simultaneous pickup and delivery: Mathematical model and heuristic approach", *Computer & Industrial Engineering*, Vol. 115, pp. 1-16.

Chen, J. F. and Wu, T. H., (2006). "Vehicle routing problem with simultaneous deliveries and pickups", *Journal of the Operational Research Society*, Vol. 57, No. 5, pp. 579-587.

Chen, Q., Li K., and Liu, Z., (2014). "Model and algorithm for unpaired pickup and delivery vehicle routing problem with split loads", *Transportation Research Part E*, Vol. 69, pp. 218-235.

Cheng, C., Yang, P., Qi, M., and Rousseau, L.M., (2017). "Modeling a green inventory routing problem with a heterogeneous fleet", *Transportation Research Part E*, Vol. 97, pp. 97-112.

Cruz, R. C., Silva, T. C. B., and Souza, M. J. F., (2012). "A heuristic approach for solving the vehicle routing problem with simultaneous pickup and delivery", *Electronic Notes in Discrete Mathematics*, Vol. 39, pp. 217-224.

Dror, M., and Trudeau, P., (1989). "Savings by split delivery routing", *Transportation Science*, pp. 141-145.

Goli, A., Babaee Tirkolaei, E., and Soltani, M., (2019). "A robust just-in-time flow shop scheduling problem with outsourcing option on subcontractors", *Production & Manufacturing Research*, Vol. 7, No. 1, pp. 294-315.

Goli, A., and Davoodi, M.R., (2018). "Coordination policy for production and delivery scheduling in the closed loop supply chain", *Production Engineering*, Vol. 12, No. 5, pp. 621-631.

Goli, A., and Davoodi, M.R., (2019). "An integrated disaster relief model based on covering tour using hybrid Benders decomposition and variable neighborhood search: Application in the Iranian context", *Computers & Industrial Engineering*, Vol. 130, pp. 370-380.

Goli, A., Khademi Zare, H., Tavakkoli Moghaddam, R., and Sadeghieh, A., (2019). "Application of robust optimization for product portfolio problem using an invasive weed optimization algorithm", *Numerical Algebra, Control and Optimization*, Vol. 9, No. 2.

Goli, A., Khademi Zare, H., Tavakkoli Moghaddam, R., and Sadeghieh, A., (2019). "Multiobjective fuzzy mathematical model for a financially constrained closed-loop supply chain with labor employment", *Computational Intelligence*, pp. 1–31.

Goli, A., Khademi Zereh, H., Tavakkoli-Moghaddam, R., and Sadeghieh, A., (2019). "Hybrid artificial intelligence and robust optimization for a multi-objective product portfolio problem Case study: The dairy products industry", *Computers & Industrial Engineering*, Vol. 137.

Huang, Y., Zhao, L., Woensel, T.V., and Gross, J.P., (2017). "Time-dependent vehicle routing problem with path flexibility", *Transportation Research Part B*, Vol. 95, pp. 169-195.

Kalayci, C. B., and Kaya, C., (2016). "An ant colony system empowered variable neighborhood search algorithm for the vehicle routing problem with simultaneous pickup and delivery", *Expert System with Applications*, Vol. 66, pp. 163-175.

Koç, Ç., and Karaoglan, I., (2016). "The green vehicle routing problem: A heuristic based exact solution approach", *Applied Soft Computing*, Vol. 39, pp. 154-164.

Lin C., Choy K. L., Ho G. T. S., Chung S. H., Lam H. T., (2013). "Survey of Green Vehicle Routing Problem: Past and future trends", *Expert Systems with Applications*, Vol. 41, pp. 1118-1163.

Madankumar, S., and Rajendran, C., (2018). "Mathematical models for green vehicle routing problems with pickup and delivery: A case of semiconductor supply chain", *Computer and Operation research*, Vol. 89, pp. 183-192.

Mehrabian, A.R., and Lucas, C., (2006). "A novel numerical optimization algorithm inspired from weed colonization", *Ecological Information*, Vol. 1, pp. 355-366.

Nagy, G., Salhi, S., (2005). "A heuristic algorithms for single and multiple depot vehicle routing problems with pickups and deliveries", *European Journal of Operational Research*, Vol. 162, pp. 126-141.

Özyurt, Z., Aksen, D., and Aras, N., (2006). "OVRP with time deadlines: solution methods and applications", OR Proceedings 2005. Springer Berlin Heidelberg, pp. 73-78.

Pachauri, R.K., Allen, M.R., Barros, Broome, J., Cramer, W., Christ, R., et al., (2014). "Climate change 2014: Synthesis report", Contribution of working groups 1, 2 and 3 to the fifth assessment report of the intergovernmental panel on climate change.

Poonthalir, G., and Nadarajan, R., (2018). "A Fuel Efficient Green Vehicle Routing Problem with varying speed constraint (F-GVRP)", *Expert Systems with Applications*, Vol. 100, pp. 131-144.

Ramezani Ghalenoei, M., Hajimirsadeghi, H., and Lucas, C., (2009). "Discrete Invasive Weed Optimization Algorithm: Application to cooperative Multiple Task Assignment of UAV's", 48^{th} IEEE Conference on decision and control.

Sangaiah, A.K., Babaee Tirkolaei, E., Goli, A., and Dehvani-Arani, S., (2019). "Robust optimization and mixed-integer linear programming model for LNG supply chain planning problem", *Soft Computing*.

Soleimani, H., Chaharlang, Y., and Ghaderi, H., (2018). "Collection and distribution of returned-remanufactured products in a vehicle routing problem with pickup and delivery considering sustainable and green criteria", *Journal of Cleaner Production*, Vol. 172, pp. 960-970.

Subramanian, A., Drummond, L. M. A., and Bentes, C., (2010). "A parallel heuristic for the vehicle routing problem with simultaneous pickup and delivery", *Computers & Operations Research*, Vol. 37, No. 11, pp. 1899-1911.

Taguchi, G., Chowdhury, S., and Wu, Y., (2005). "Taguchi's Quality Engineering Handbook", Volume 1736. Hoboken, NJ: John Wiley & Sons, Inc.

Tasan, A.S., Gen, M., (2012). "A genetic algorithm based approach to vehicle routing problem with simultaneous pick-up and deliveries", *Computers & Industrial Engineering*, Vol. 62, No. 3, pp. 755-761.

Thangiah, S., Vinayagamoorty, R., and Gubbi A., (1993). "Vehicle routing and time deadlines using genetic and loca algorithms", Proceedings of the 5th International Conference on Genetic Algorithms, pp. 506-515.

Turkensteen, M., and Hasle, G., (2017). "Combining pickups and deliveries in vehicle routing – An assessment of carbon emission effects", *Transportation Research Part C: Emerging Technologies*, Vol. 80, pp. 117-132.

Ubeda, S., Arcelus, F. J., and Faulin, J., (2011). "Green logistics of vehicle routing problem", *Vehicle routing problem*, Vol. 9, pp. 1-26.

Wang, X., and Li, X., (2018). "Carbon reduction in the location routing problem with heterogeneous fleet, simultaneous pickup-delivery and time windows", *Procedia Computer Science*, Vol. 112, pp. 1131-1140.

Xiao, Y., and Konak, A., (2016). "The heterogeneous green vehicle routing and scheduling problem with time varying traffic congestion", *Transportation Research Part E*, Vol. 88, pp. 146-166.

Xiao, Y., Zhao, Q., Kaku, I., and Xu, Y., (2012). "Development of a fuel consumption optimization model for the capacitated vehicle routing problem", *Computers and Operations Research*, Vol. 39, Vol. 7, pp. 1419-1431.

Zachariadis, E. E., Tarantilis, C. D., and Kiranoudis C. T., (2009). "A hybrid metaheuristic algorithm for the vehicle routing problem with simultaneous delivery and pick-up service", *Expert Systems with Applications*, Vol. 36, No. 2, pp. 1070-1081.

Zhang, S., Lee, C.K.M., Choy, K.L., Ho, W., and Ip, W.H., (2014). "Design and development of a hybrid artificial bee colony algorithm for the environmental vehicle routing problem", *Transportation Research Part D*, Vol. 31, pp. 85-99.

This article can be cited: Sadat Hosseini Khajouei, M.H., Pilevari, N., (2021). "Developing an environmental vehicle routing problem with simultaneous pickup and delivery: Mathematical model and a discrete invasive weed optimization approach", *Journal of Industrial Engineering and Management Studies*, Vol. 8, No. 1, pp. 202-217.