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A Multi-Objective Optimization Model for Split Pollution Routing Problem with Controlled Indoor Activities in Cross Docking under Uncertainty

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Abstract *– Cross docking is a logistics strategy that strives to reduce inventory holding costs, shipping costs, and delays in delivering the products. In this research, an optimization model is presented for split loading and unloading products by suppliers and customers, vehicle routing with fuzzy possibilistic time window constraints among them, assignment of vehicles to cross dock, consolidation and integration of products in cross dock, and allocation of sorted products to outbound vehicles. The mathematical model provided in this study has three objective functions. The first and second objectives minimize total cost and fuel consumption, and the third one maximizes satisfaction degrees of suppliers and customers. With the intention of solving the model, two multi-objective meta-heuristic algorithms, namely Multi-Objective Grey Wolf Optimizer (MOGWO) and Multi-Objective Imperialist Competitive Algorithm (MOICA) were utilized. With the intention of illustrating the accuracy of the suggested model and solution approaches, a broad range of numerical instances were considered and the results were investigated.*

Keywords *– Consolidation, Cross docking, Integration, Satisfaction, Split pickup and delivery.*

I. INTRODUCTION

One of the significant issues, which contributes to enhancing the reputation of the supply chain, is competitive surrounding of the world marketplace. Accompanied by an increase in the pressure on providers and wholesalers to expedite the transfer of products to clienteles and a broad range of merchandises needed by clienteles globally, companies are striving to develop a strategy for distributing and improving their supply chain performance. An innovative approach to responding promptly to customer demand and reducing inventory levels of needless merchandises is cross dock. A cross dock is considered as an intermediate node between distribution midpoints and clienteles. There are 5 crucial functions for a distribution center, which are receiving, sorting, storing, retrieving, and shipment (Yu, 2002; Ye et al., 2018a). A cross dock has the potential to decline expenses and improve efficiency by eliminating two storage and retrieval operations that, in turn, increase holding costs and the value of labor in distribution centers (Tanaka et al., 2018; Mousavi et al., 2019). In general, in a cross dock, merchandises are shipped in a straight line from the inbound truck to the outbound truck with the least possible storage. The time the products are present in a dock between the receiving and shipping doors is typically less than 24 hours and sometimes less than 1 hour (Yu and Egbelu, 2008).

Scientific research has considered 3 levels of decision making in the cross-docking system, including operational, tactical, and strategic (Larbi et al., 2011; Ye et al., 2018b; Bhangu et al., 2019). Longitudinal plans, such as the location of cross docking, design, and configuration, are the main strategic decisions in the planning of a cross-docking system. Mid-term plans, such as distributing and supplying, are the main tactical decisions and short-term plans, such as vehicle routing and scheduling, are the main operational decisions (Ahkamiraad and Wang, 2018; Heidari et al., 2018).

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One of the crucial activities, which is related to the planning of a cross-docking system, is sorting the merchandises, which are entered into the cross dock by inbound trucks and categorized based on the demands of customers, and then, loading them onto the outbound trucks in order to deliver to customers (Agustina et al., 2014; Mousavi and Vahdani, 2016, 2017; Shaelaie et al., 2018). In the literature, these activities are called integration and consolidation processes. Employing these processes is the main difference of cross-docking systems from the traditional warehouses, which can lead to diminishing logistics expenses. In fact, when sequential activities of one merchandise are served by an administrative agent, the integration process is conducted. On the other hand, when the identical activities of different merchandises are served by an administrative agent, the consolidation process is conducted. These processes could diminish the costs and time of sorting operations inside cross dock and enhance the utilization of the current resources (Zhou and Zhang, 2017). Therefore, by considering the above-mentioned approaches, the owners of companies could decline the final price of their products and enhance their competitive capabilities (Apte and Viswanathan, 2000; Vahdani et al., 2012b). However, these considerations have rarely been studied in the literature.

The other aspect of the supply chain activities, which can influence the final price of the merchandise, is the planning of transportation (Musa et al., 2010). Hence, the management of the transportation fleet, such as structuring, scheduling, and routing, can support the owners of companies in achieving their goals (Tajik et al., 2014; Vahdani and Zandieh, 2010). Furthermore, guaranteeing sustainable improvement of each community is closely related to maintaining and adjusting the utilization of limited available resources. From this perspective, governments factor in a broad range of activities, such as reducing utilization of fossil resources and increasing the use of environmentally friendly raw materials in different stages of the supply chain, e.g., manufacturing, distributing, etc. (Niu et al., 2018). Consequently, we are faced with a new concept of supply chain management, called green supply chain, which can create new worth for various members of supply chain by diminishing contamination or elimination of wastes (Toro et al., 2017; Vahdani et al., 2012a). Since the transportation activities would have irreversible influences on the environment, such as noise and emissions of greenhouse gases, we need to control the side effects of these activities. One of the critical measures in this matter is to consider pollution routing problem in the planning of transportation fleet (Huang et al., 2012; Park and Chae, 2014). In addition, one of the most critical components in promoting business activities is to obtain customer satisfaction. Typically, to calculate customer satisfaction, only customers of the end product are considered. However, in cross docking, in addition to customers who are classically satisfied, suppliers' consent should also be provided. Therefore, the total outcome of these two types of satisfaction should be considered as the satisfaction of the entire cross-docking system.

The issue under consideration can have many applications in the real world. For example, this research can be used for the supply chain of food products, especially those that should be carried at a low temperature and their freshness is vital for the customers. Due to the extensive supply of these products, they need to be well planned by the manufacturers. Therefore, considerations should be given to routing the vehicles of transport. Due to the limited capacity of vehicles for these products, we need to use a split approach if there is a need to supply a high volume of demand. With regard to the nature of these types of products, the timing of this operation in cross docking is also crucial. Therefore, considerations should also be given to the activities inside cross docking. Indeed, there are similar cases in the delivery process, e.g., in the pickup process, for which we also consider the delivery process. Also, the environmental concerns of this process are considered, which can affect the satisfaction of regulatory agencies as well as customers. On the other hand, pickup and delivery times of these products have a significant impact on the satisfaction of suppliers and customers. It is noteworthy that since these times are uncertain for suppliers and customers, we use the fuzzy set theory to overcome this uncertainty. Also, since the final customer satisfaction may be of higher importance to the satisfaction of managers, we use the weighing approach to satisfying each one of them.

A truck scheduling problem with resource constraint was investigated by Shakeri et al. (2012). They defined a bi-level heuristic approach to solving the defined problem. This solution approach consisted of two heuristics for sequencing and allocating vehicles. The other research on the truck scheduling problem was carried out by Konur and Golias (2013) in which the entrance of the trucks was unknown. They proposed a multi-objective model and a heuristic approach in order to investigate the defined problem. Bodnar et al. (2015) examined a specific multi-door scheduling truck problem in cross docking in which operational costs and truck delay costs were minimized. Also, conditioning time windows constraint was another novel aspect of this research. A variable neighborhood search algorithm was also presented to solve the aforementioned problem.

The concept of fixed time of truck departure was investigated by Rahmanzadeh tootkaleh et al. (2016). This study was aimed at finding the best sequence of inbound trucks concerning a fixed time departure. An enhanced heuristic algorithm was presented to solve the defined problem. A multiple-product truck scheduling problem was introduced by Tavana et al. (2017) in which the navigation of vehicles was considered. Also, a novel multi-objective epsilon-constraint approach was developed with the intention of solving the proposed model. Integrating cross docking and vehicle routing was investigated by Wen et al. (2009). In this study, a mathematical model was introduced in order to minimize the total travel time of vehicles. Finally, a Tabu search meta-heuristic algorithm was presented to solve the above problem. Another research concerning cross docking and vehicle routing problem was conducted by Liao et al. (2010). This study was aimed at determining the number of vehicles and minimizing the total costs. Also, they presented a Tabu search meta-heuristic algorithm to solve the above problem.

A multi-stage, multi-product logistics network was addressed in order to synchronize the planning of cross docking and vehicle routing problem by Dondo et al. (2011). This study factored in satisfaction of the customer and minimized the total transportation costs. The concept of renting a vehicle in cross docking and vehicle routing was examined by Vincent et al. (2016). This research was aimed at minimizing total transportation costs. Also, they presented a simulated annealing meta-heuristic approach to solving the above problem. The primary research on green vehicle routing in a cross-docking environment was presented by Yin and Chuang (2016). Green and environmental concerns in this model are considered as a constraint of a mathematical model. They presented a bee colony algorithm to solve the above problem.

The primary research on split vehicle routing in a cross-docking environment was presented by Wang et al. (2017), in which split delivery was allowable. A new mathematical model, in order to minimize total transportation and fixed costs of vehicles, was developed. Moreover, a bi-level heuristic approach based on simulated annealing and Tabu search algorithms was proposed to solve the formulated problem.

An integrated vehicle routing problem considering assignment of vehicles to the doors of cross docking was presented by Enderer et al. (2017). Also, an exact heuristic method was utilized to solve the formulated model. Abad et al. (2018) investigated a cross-docking environment and green vehicle routing problem in which integration and consolidation of merchandises were considered. Moreover, they proposed two multi-objective meta-heuristics in order to solve the proposed model. To show the research gap and the novelty of the current research, a categorical analysis is provided in Table I.

As can be seen in Table I, no research has ever investigated the satisfaction degree of suppliers and customers in the cross-docking system by considering split pollution routing problem with controlled indoor activities. Also, a limited number of studies are concerned with environmental and uncertain issues in vehicle routing in a cross dock. Thus, the mathematical model provided in this study has three objective functions. The first and second objectives minimize total cost and fuel consumption, and the third one maximizes satisfaction degrees of suppliers and customers. In order to solve the model, two multi-objective meta-heuristic algorithms, namely Multi-Objective Imperialist Competitive Algorithm (MOICA) and Multi-Objective Grey Wolf Optimizer (MOGWO), are utilized.

The remaining of this paper is structured as follows. In Section II, problem definition and formulation are provided. The solution methodologies are given in Section III. Numerical results are demonstrated in Section VI. Finally, the conclusions and future research directions are provided in Section V.

Table I. A summary of the literature review

Author(s) and year	Environment		Outdoor cross dock					Indoor cross dock		Objective function		Solution approach			Satisfaction degree		Uncertainty
	Green/ Sustainable	Classical	Vehicle routing			Truck/ operation scheduling	Door assignment	Integration	Consolidation	Single	Multiple	Exact /GAMS/ CPLEX	Meta-heuristic	Heuristic	Supplier (s)	Customer (s)	
			Non-split	Split delivery	Split pickup												
Shakeri et al. (2012)		✓				✓	✓			✓				✓			
Konur and Golias (2013)		✓				✓	✓			✓			✓	✓			
Bodnar et al. (2015)		✓				✓	✓			✓				✓			
Tootkaleh et al. (2016)		✓				✓	✓			✓				✓			
Tavana et al. (2017)		✓				✓	✓				✓	✓					
Wen et al. (2009)		✓	✓						✓	✓				✓			
Liao et al. (2010)		✓	✓							✓			✓				
Dondo et al. (2011)		✓	✓			✓					✓	✓				✓	
Vincent et al. (2016)		✓	✓							✓			✓				
Yin and Chuang (2016)	✓		✓							✓			✓				
Wang et al. (2017)		✓		✓						✓				✓			
Oh et al. (2006)		✓					✓			✓			✓	✓			
Liao et al. (2013)		✓				✓	✓			✓			✓				
Kuo (2013)		✓				✓	✓			✓			✓				
Enderer et al. (2017)		✓	✓				✓			✓		✓		✓			
Wisittipanich and Hengmeechai (2017)		✓				✓	✓			✓			✓				
Abad et al. (2018)	✓		✓			✓		✓	✓		✓		✓				
Baniamerian et al. (2019)		✓	✓			✓				✓			✓				
The current research	✓			✓	✓	✓		✓	✓		✓		✓		✓	✓	✓

II. PROBLEM DEFINITION

In this research, three main stages are considered. First, products of the suppliers are collected by vehicles, which is called the pickup process. Then, the products are transported to the cross-docking system to conduct the essential activities including inspection, consolidation, and integration. It should be noted that these processes are typically performed in various stages among various operational stations based on customer demands. The integration processcan be gone through if at least two activities on one received product have been performed by an administrative agent. Similarly, consolidation process can be passed if all identical activities on at least two dissimilar received products have been done by an administrative agent. These processes can reduce the costs and time of operation by executive agents (Zhou and Zhang, 2017). Then, the packed shipments are transported to customers by vehicles. Moreover, due to the uncertainty in predicting preferable time windows of suppliers and customers, a fuzzy possibilistic programming approach is considered.

On the other hand, the pickup and delivery times of products have a significant impact on the satisfaction of suppliers and customers. Therefore, considering satisfaction degrees based on time windows and arrival time of products would enhance the accuracy of planning. Hence, the lower difference between time windows and arrival times for suppliers and customers, the higher the degrees of their satisfaction will be. In order to deal with this issue, an exponential function is considered for computing the satisfaction degrees of suppliers and customers, which comprises a comparative difference between time window and arrival time. It should be noted that since time window is usually uncertain for suppliers and customers, we use the fuzzy set theory to overcome this uncertainty. Also, since the final customer satisfaction may be of higher importance to managers, we use the weighing approach.

In order to formulate the defined problem, there are some assumptions, which are presented as follows:

- The positions of the suppliers and customers are pre-defined.
- Each supplier could supply only one type of product
- The capacity of supply for each supplier is known before the beginning of the planning horizon.
- To serve the pickup and delivery processes, a limited number of homogenous vehicles with specified identical capacities are regularly utilized.
- All the vehicles that are used in the pickup and delivery processes, after departing the cross dock, should return to it.
- Different vehicles are considered for the pickup and delivery processes.
- Split pickup and delivery are permissible with the capacity of vehicles.
- The number of administrative agents in cross dock is predefined before the beginning of the planning horizon.
- Since different products require a broad range of various services, each of the administrative agents is able to perform multiple activities.
- The number of required activities for different products is predefined and the same.
- Each administrative agent can offer service for a specific activity on a product.
- Each activity needs setup time and is considered to complete the activities on each product.

An all-inclusive approach to computing fuel emissions is applied, which was presented by Barth et al. (2005). Through this approach, we can calculate the fuel consumption of vehicle k across distance d as follows:

$$\mathcal{F}^k = \lambda\left(\frac{\mathcal{K}^k \mathcal{N}^k \mathcal{V}^k d}{v} + \mathcal{J}^k \chi^k \sigma d + \rho^k \chi^k d v^2\right) \tag{1}$$

where $\chi^k = 1/1000 n_{te}\eta$, $\lambda = \xi/\mathcal{k}\psi$, $\rho^k = 0.5C_d^k \mu \mathcal{A}^k$, and $\sigma = \tau + g sin\theta + g C_r cos\theta$. Also, $\mathcal{J}^{\mathrm{k}}$ represents the total weight of the vehicle and the speed of the vehicle is denoted by v. The other parameters are listed in Table II.

Table II. The parameters in computing fuel consumption of a vehicle

Symbol	***Explanation***	***Value***
ξ	Mass ratio of fuel to air	1
g	Gravitational constant (m/s^2)	9.81

Symbol	***Explanation***	***Value***
μ	Density of air (kg/m^2)	1.2041
C_r	Rolling resistance coefficient	0.01
η	Efficiency of diesel engine	0.45
$\mathscr{f}_d$	Driver wage (RMB/s)	0.0111
$\mathscr{k}$	Heating value $(kj/\mathscr{g})$	44
ψ	Factor of conversion ($\mathscr{g}$ /s to L/s)	737
n_{te}	Efficiency of vehicle drive train	0.45
v^l	Lower speed (m/s)	2
v^u	Upper speed (m/s)	27.8 (or 100 km/h)
$\mathscr{w}$	Curb weight (kg)	6350
$\mathcal{K}$	Factor of engine friction $(kj/rev/\ liter)$	0.23
$\mathcal{N}$	Engine speed (rev/s)	37
$\mathcal{V}$	Displacement of the engine $(liter)$	5
C_d	Aerodynamics drag coefficient	0.7
$\mathcal{A}$	Frontal surface area (m^2)	3.912

A. Sets and indices

Sets:

N: Suppliers

M: Customers

N': Cross dock and suppliers

M': Cross dock and customers
E: Arcs among suppliers
E' : Arcs among customers

K_1: Vehicles of suppliers

K_2: Vehicles of Customers

P: Products

A: Agents of the cross dock

B: Activities

$\mathcal{R}$: Speed of vehicles
$\pi_{\mathscr{q}}$: Integration
$\theta_{\mathscr{u}}$: Consolidation
Indices

i, j: Suppliers and customers

0: Cross dock

k, k': Vehicles

p: Products

l: Agents

g: Activities
r: Speed
q: Possible integration
u: Possible consolidation

B. Parameters

v_{ip}: The volume of product p which is produced by supplier i

α_p: The volume of space which is engaged in the pickup process by product p

γ_p: The volume of space which is engaged in the delivery process by product p

$\mathcal{D}_{ip}$: The volume of product p which is demanded by customer i

$\mathcal{C}$: Capacity of vehicle

t_{lpb}: Processing time of administrative agent l to perform activity g on product p

c_{ij}^{k}: Transportation cost between suppliers i, j in pickup process and cross dock by vehicle k

$c_{ij}^{k'}$: Transportation cost between customers i, j in the delivery process and cross dock by vehicle k'

$st_{q,g}^{int}$: Setup time of the gth activity for a product in π_q

$\mathcal{S}_{lg}^{p}$: Setup cost of activity g for product p, which is assigned to agent l

$\mathcal{P}_{lg}^{p}$: The cost of processing of activity g for product p, which is assigned to agent l

ζ_n: Incremental time of setup for consolidation

scs_{q}^{int}: Setup cost for integration in π_q

cs_{u}^{con}: Cost of consolidation in θ_u

pt_i: Time of picking up products from supplier i

dt_i: Time of delivering products to customer i

$\widetilde{ep}_i$: Fuzzy earliest time of pickup from supplier i

$\widetilde{ed}_i$: Fuzzy earliest time of delivery to customer i

$\widetilde{lp}_i$: Fuzzy latest time of pickup from supplier i

$\widetilde{ld}_i$: Fuzzy latest time of delivery to customer i

w_i : Satisfaction weight in the pickup process

w_i' : Satisfaction weight in the delivery process

q_{ip}: 1 if supplier i supplies product p; 0 otherwise $\left(\sum_{p\in P} q_{ip} = 1 \ \ \forall i \in N\right)$

ℓ_{ip}: 1 if customer i requires product p; 0 otherwise

d_{ij}: The distance in arc i, j

h_q: The entire number of activities in π_q

e_u: The entire number of activities in θ_u

$\overline{v}^r$: Non-reducing speed levels

$\mathcal{M}$: A big number

C. Decision variables

$\mathcal{X}_{ij}^{k}$: 1 if vehicle k travels through arc i,j in the pickup process; 0 otherwise

$\mathcal{X}_{ij}^{k'}$: 1 if vehicle k'travels through arc i,j in the delivery process; 0 otherwise

$\mathcal{Y}_{lg}^{p}$: 1 if activity g on product p is accomplished by the administrative agent l; 0 otherwise

$\mathcal{Z}_{q}$: 1 if a products in π_{q} are integrated by a specific administrative agent; 0 otherwise

$\mathcal{W}_u$: 1 if products in θ_u are consolidated by a specific administrative agent; 0 otherwise

$\mathcal{Q}_{ij}^{kr}$: 1 if vehicle k travels through arc i,j with speed r in the pickup process

$\mathcal{Q}_{ij}^{k'r}$: 1 if the vehicle k' travels through arc i,j with speed r in the delivery process

$\mathcal{AT}_{ik}$: Time of arrival of vehicle k in pickup process at supplier i

$\mathcal{AT}_{ik'}$: Time of arrival of vehicle k' in the delivery process at customer i

$\mathcal{ATC}_k$: Time of arrival of vehicle k at cross dock

$\mathcal{E}_u^1$: The longest time of processing

$\mathcal{E}_u^2$: The latest completion time of processing

$\mathcal{CT}_{gp}$: Time of completion after activity g on product p

$\mathcal{RT}_p$: Ready time of product p to deliver to customers

$\mathcal{H}_{ij}$: Total volume of flow in arc i,j

D. Mathematical model

$$Min\ Z_1 = \sum_{i\in N'}\sum_{j\in N'}\sum_{k\in K_1} c_{ij}^{k}\mathcal{X}_{ij}^{k} + \sum_{i\in M'}\sum_{j\in M'}\sum_{k'\in K_2} c_{ij}^{k'}\mathcal{X}_{ij}^{k'} + \sum_{l\in A}\sum_{p\in P}\sum_{g\in B}\left(\mathcal{S}_{lg}^{p} + \mathcal{P}_{lg}^{p}\right)\mathcal{Y}_{lg}^{p} - \sum_{q\in\pi_{q}} \mathcal{sc}\mathcal{s}_{q}^{int}\mathcal{Z}_{q} - \sum_{u\in\theta_u} c\mathcal{s}_{u}^{con}\mathcal{W}_u + \sum_{i\in N'}\sum_{j\in N'}\sum_{k\in K_1} \mathcal{f}_d\, d_{ij}\mathcal{X}_{ij}^{k}/v + \sum_{i\in M'}\sum_{j\in M'}\sum_{k'\in K_2} \mathcal{f}_d d_{ij}\mathcal{X}_{ij}^{k'}/v \tag{2}$$

The first objective function minimizes the total costs, in which transportation costs in the pickup and delivery processes are computed by the first and second terms in Eq. (2). The setup and operation costs, which are related to the activities inside the cross-dock, are calculated by the third term. The saving costs, which are obtained by the integration and consolidation processes, are computed by the fourth and fifth terms. Finally, driver costs in the pickup and delivery processes are computed by the sixth and seventh terms.

$$Min\ Z_2 = \sum_{i\in N'}\sum_{j\in N'} \lambda\mathcal{KNV}d_{ij}\sum_{k\in K_1}\sum_{r\in\mathcal{R}} \mathcal{Q}_{ij}^{kr}/\overline{v}^r + \sum_{i\in N'}\sum_{j\in N'}\sum_{k\in K_1}\lambda\chi^k\sigma_{ij}\, d_{ij}\left(w\mathcal{X}_{ij}^{k} + \mathcal{H}_{ij}\right) + \sum_{i\in N'}\sum_{j\in N'}\sum_{k\in K_1}\lambda\rho^k d_{ij}\,\chi^k d_{ij}\sum_{r\in R}\left(\overline{v}^r\right)^2 \mathcal{Q}_{ij}^{kr} + \sum_{i\in M'}\sum_{j\in M'}\lambda\mathcal{KNV}d_{ij}\sum_{k'\in K_2}\sum_{r\in\mathcal{R}}\mathcal{Q}_{ij}^{k'r}/\overline{v}^r + \sum_{i\in M'}\sum_{j\in M'}\sum_{k'\in K_2}\lambda\chi^k\sigma_{ij}\, d_{ij}\left(w\mathcal{X}_{ij}^{k'} + \mathcal{H}_{ij}\right) + \sum_{i\in M'}\sum_{j\in M'}\sum_{k'\in K_2}\lambda\rho^k d_{ij}\,\chi^k d_{ij}\sum_{r\in R}\left(\overline{v}^r\right)^2 \mathcal{Q}_{ij}^{k'r} \tag{3}$$

Fuel consumption of the vehicles is minimized by the second objective function, which contributes to a decrease in greenhouse gases emission. The fuel consumption in the pickup process is calculated by the first to third terms in Eq. (3). The same calculations for the delivery process are conducted by fourth to sixth terms.

$$Max\ Z_3 = \sum_{i\in N}\sum_{k\in K_1} w_i . e^{\frac{\mathcal{AT}_{ik}-\widetilde{ep}_i}{\widetilde{lp}_i-\widetilde{ep}_i}} + \sum_{i\in M}\sum_{k'\in K_2} w'_i . e^{\frac{\mathcal{AT}_{ik'}-\widetilde{ed}_i}{\widetilde{ld}_i-\widetilde{ed}_i}} \quad (4)$$

The third objective function maximizes satisfaction degrees of suppliers and customers. The first term computes satisfaction degree in the pickup process. Likewise, the second one represents the satisfaction degree in the delivery process. It should be noted that the importance of satisfaction is considered different between suppliers and customers.

$$\sum_{i\in N'}\sum_{k\in K_1}\mathcal{X}_{ij}^{k} \geq 1 \qquad \forall j\in N \quad (5)$$

$$\sum_{j\in N'}\sum_{k\in K_1}\mathcal{X}_{ij}^{k} \geq 1 \qquad \forall i\in N \quad (6)$$

$$\sum_{j\in N'} q_{ip}\mathcal{X}_{ij}^{k} = \sum_{j\in N'} q_{ip}\mathcal{X}_{ji}^{k} \qquad \forall i\in N', k\in K_1, p\in P \quad (7)$$

Each node in the pickup process can receive service by at least one vehicle and the identical vehicle can leave the visited node for the following endpoint node as stated by constraints (5) and (6). Sequential travels of vehicles in the pickup process are determined by constraint (7), which prevents moving back and forth between two pickup nodes. Since ($\sum_{p\in P} q_{ip} = 1 \ \ \forall i \in N$), each supplier can supply one type of product and each vehicle only loads it.

$$\sum_{j\in N}\mathcal{X}_{0j}^{k} \leq 1 \qquad \forall\, k\in K_1 \quad (8)$$

$$\sum_{i\in N}\mathcal{X}_{i0}^{k} \leq 1 \qquad \forall\, k\in K_1 \quad (9)$$

$$\sum_{k\in K_1}\mathcal{X}_{ij}^{k} \leq 1 \qquad \forall\,(i,j)\in E \quad (10)$$

$$\sum_{i\in N'}\mathcal{X}_{ij}^{k} \leq 1 \qquad \forall\, k\in K_1, j\in N \quad (11)$$

In the pickup process, each vehicle can leave cross dock for at most one supplier, which is specified by constraint (8). Also, this compels all vehicles to begin the process of picking from the cross dock. The compulsion on vehicles to return to cross dock after pickup process is represented by constrain (9). Performing the pickup process in each route by one vehicle is ensured by (10). In the pickup process, each vehicle can visit each node once, which is indicated in constraint (11).

$$\sum_{j\in N}\mathcal{H}_{ij} - \sum_{j\in N}\mathcal{H}_{ji} = \sum_{p\in P} q_{ip}v_{ip} \qquad \forall i,j\in N' \quad (12)$$

$$\sum_{p\in P}\left(v_{ip}q_{ip}\alpha_p\right)\sum_{k\in K_1}\mathcal{X}_{ij}^{k} \leq \mathcal{H}_{ij} \leq \left(\mathcal{C} - \sum_{p\in P} v_{ip}q_{ip}\alpha_p\right)\sum_{k\in K_1}\mathcal{X}_{ij}^{k} \qquad \forall i,j\in N' \quad (13)$$

The volume moved between suppliers in the pickup process is indicated in constraints (12) and (13). Also, constraint (12) indicates that the volume moved between two suppliers should be equal to the produced products by the identical supplier. Capacity and occupied space by a vehicle are represented by constraint (13).

$$-\mathcal{AT}_{jk} + \mathcal{AT}_{ik} + \left(\sum_{r\in\mathcal{R}} d_{ij}\mathcal{Q}_{ij}^{kr}/\bar{v}^{r}\right) + pt_i \leq \left(1-\mathcal{X}_{ij}^{k}\right)\cdot\mathcal{M} \qquad \forall i,j\in N', k\in K_1 \quad (14)$$

$$-\mathcal{ATC}_k + \mathcal{AT}_{ik} + \left(\sum_{r\in\mathcal{R}} d_{i0}\mathcal{Q}_{i0}^{kr}/\bar{v}^{r}\right) + pt_i \leq \left(1-\mathcal{X}_{i0}^{k}\right)\cdot\mathcal{M} \qquad \forall i\in N, k\in K_1 \quad (15)$$

Pickup process duration by vehicle among suppliers is computed by constraint (14). Also, the time of arrival of the vehicle at cross dock in the pickup process from the last node assigned to it is calculated by constraint (15).

$$\sum_{r\in\mathcal{R}}\mathcal{Q}_{ij}^{kr} = \mathcal{X}_{ij}^{k} \qquad \forall i,j\in N', k\in K_1 \quad (16)$$

$$\widetilde{ep}_i \leq \mathcal{AT}_{ik} \leq \widetilde{lp}_i \qquad \forall i\in N, k\in K_1 \quad (17)$$

Each vehicle, in order to transport among pickup nodes, can select only one speed level, which is determined by constraint (16). Also, fuzzy time windows constraints, which are applied to the arrival times of the vehicle at the pickup nodes, are considered in constraint (17).

$$\mathcal{Y}_{lg}^{p} \leq q_{ip}\mathcal{X}_{ij}^{k} \qquad \forall p \in P, g \in B, l \in A, i, j \in N \tag{18}$$

$$\sum_{l\in A}\mathcal{Y}_{lg}^{p} = 1 \qquad \forall p \in P, g \in B \tag{19}$$

$$\mathcal{Z}_{q} \leq \mathcal{Y}_{lg}^{p} \qquad \forall \text{ assignment } \mathcal{Y}_{lg}^{p} \text{ in } \pi_{q} \tag{20}$$

$$\mathcal{W}_{u} \leq \mathcal{Y}_{lg}^{p} \qquad \forall \text{ assignment } \mathcal{Y}_{lg}^{p} \text{ in } \theta_{u} \tag{21}$$

The administrative agent can perform the required activities on each product. If a product is assigned to a specific agent, it is supplied by the supplier and burdened by vehicles to the cross dock, as indicated in constraint (18). Also, each activity on each product can be performed by only one administrative agent, which is ensured by constraint (19). Integration and consolidation processes for a product are assigned to the administrative agent (Zhou and Zhang, 2017; Abad et al., 2018).

$$\sum_{\text{assignments in } \pi_{q}} \mathcal{Y}_{lg}^{p} - h_{q} + 1 \leq \mathcal{Z}_{q} + \sum_{\pi_{q''} \text{ contains } \pi_{q}} \mathcal{Z}_{q''} \qquad \forall \text{ integration set } \pi_{q} \tag{22}$$

$$\sum_{\text{sub−integraions } \pi_{q'} \text{ in } \pi_{q}} \mathcal{Z}_{q'} \leq \left(1 - \mathcal{Z}_{q}\right) \cdot \mathcal{M} \qquad \forall \text{ integration set } \pi_{q} \tag{23}$$

$$\sum_{\text{assignments in } \theta_{u}} \mathcal{Y}_{lg}^{p} - e_{u} + 1 \leq \mathcal{W}_{u} + \sum_{\theta_{u''} \text{contains } \theta_{u}} \mathcal{W}_{u''} \qquad \forall \text{ consolidation set } \theta_{u} \tag{24}$$

$$\sum_{\text{sub−consolidations } \theta_{u'} \text{in } \theta_{u}} \mathcal{W}_{u'} \leq (1 - \mathcal{W}_{u}) \cdot \mathcal{M} \qquad \forall \text{ consolidation set } \theta_{u} \tag{25}$$

Constraints (22) and (23) ensure that the process of integration, in which some equational activities are integrated, is regulated by the corresponding tasks of the basic components. Also, sub-combinations will not be assigned if multiple activities are integrated. Constraints (24) and (25) assure the same conditions for the consolidation process. Moreover, constraint (26) should be satisfied through withdrawing the corresponding time savings from the completion time of activity if the task involves integration (Zhou and Zhang, 2017; Abad et al., 2018).

$$\sum_{l\in A}\mathcal{Y}_{lg}^{p}\, t_{lpb} - \sum_{\mathcal{Y}_{lg}^{p}\in\pi_{q}} st_{qg}^{int}\, \mathcal{Z}_{q} + \mathcal{CT}_{(g-1)p} \leq \mathcal{CT}_{gp} \qquad \forall g \in B, p \in P \tag{26}$$

$$\mathcal{E}_{u}^{1} \geq t_{lpb}\mathcal{W}_{u} \tag{27}$$

$$\mathcal{E}_{u}^{2} \geq \mathcal{CT}_{(g-1)p} - (1 - \mathcal{W}_{u}) \cdot \mathcal{M} \tag{28}$$

$$\mathcal{M} \cdot (\mathcal{W}_{u} - 1) + \mathcal{E}_{u}^{1} + \mathcal{E}_{u}^{2} + \zeta_{n}\mathcal{W}_{u} \leq \mathcal{CT}_{gp} \tag{29}$$

$$\mathcal{CT}_{\vartheta p} \leq \mathcal{RT}_{p} \tag{30}$$

Calculation of the longest processing time for an activity of consolidating products is indicated in constraint (27). Constraint (28) computes the latest time of completion of the other activity for consolidating products. Calculation of the completion time of an activity for consolidating products is presented in constraint (29).

$$\sum_{i\in M'}\sum_{k'\in K_2}\mathcal{X}_{ij}^{k'} \geq 1 \qquad \forall j \in M \tag{31}$$

$$\sum_{j\in M'}\sum_{k'\in K_2}\mathcal{X}_{ij}^{k'} \geq 1 \qquad \forall i \in M \tag{32}$$

Each node in the delivery process can receive service by at least one vehicle, and the identical vehicle can leave the visited node for the following destination node, as specified by constraints (31) and (32).

$$\sum_{j\in M'} \ell_{ip}\mathcal{X}_{ij}^{k'} = \sum_{j\in M'} \ell_{ip}\mathcal{X}_{ji}^{k'} \qquad \forall i \in M', k' \in K_2, p \in P \tag{33}$$

$$\sum_{j\in M} \mathcal{X}_{0j}^{k'} \leq 1 \qquad \forall\, k' \in K_2 \tag{34}$$

$$\sum_{i\in M} \mathcal{X}_{i0}^{k'} \leq 1 \qquad \forall\, k' \in K_1 \tag{35}$$

$$\sum_{k'\in K_2} \mathcal{X}_{ij}^{k'} \leq 1 \qquad \forall\, (i,j) \in E' \tag{36}$$

$$\sum_{i\in M'} \mathcal{X}_{ij}^{k'} \leq 1 \qquad \forall\, k' \in K_2, j \in M \tag{37}$$

Sequential travels of vehicles in the delivery process are guaranteed by constraint (33), avoiding moving back and forth between two delivery nodes.

In the delivery process, each vehicle can leave cross dock for at most one customer, which is indicated in constraint (34). Also, this compels all vehicles to begin the process of picking from the cross dock. The compulsion on the vehicles to return to cross dock after delivery process is represented in constraint (35). Performing the delivery process in each route by one vehicle is ensured by (36). In the delivery process, each vehicle can visit each node once, which is indicated in constraint (37).

$$\sum_{j\in M} \mathcal{H}_{ij} - \sum_{j\in M} \mathcal{H}_{ji} = \sum_{p\in P} \ell_{ip}\, \mathcal{D}_{ip} \qquad \forall i,j \in M' \tag{38}$$

$$\sum_{p\in P}\left(\mathcal{D}_{ip}\ell_{ip}\gamma_p\right) \sum_{k'\in K_2} \mathcal{X}_{ij}^{k'} \leq \mathcal{H}_{ij} \leq \left(\mathcal{C} - \sum_{p\in P} \mathcal{D}_{ip}\ell_{ip}\gamma_p\right) \sum_{k'\in K_2} \mathcal{X}_{ij}^{k'} \qquad \forall i,j \in M' \tag{39}$$

The volume moved between customers in the delivery process is indicated in constraints (38) and (39). Also, constraint (38) indicates that the volume moved between two customers should be equal to the demand of the customer. Capacity of the vehicle and occupied space are represented by constraint (39) (Abad et al., 2018).

$$-\mathcal{AT}_{jk'} + \max_{p} \mathcal{RT}_p\ell_{ip} + \left(\sum_{r\in\mathcal{R}} d_{0j}\mathcal{Q}_{0j}^{k'r} / \overline{v}^r\right) \leq \left(1 - \mathcal{X}_{0j}^{k'}\right)\cdot \mathcal{M} \qquad \forall j \in M', k' \in K_2 \tag{40}$$

$$-\mathcal{AT}_{jk'} + \mathcal{AT}_{ik'} + \left(\sum_{r\in\mathcal{R}} d_{ij}\mathcal{Q}_{ij}^{k'r} / \overline{v}^r\right) + dt_i \leq \left(1 - \mathcal{X}_{ij}^{k'}\right)\cdot \mathcal{M} \qquad \forall i,j \in M', k' \in K_2 \tag{41}$$

$$\sum_{r\in\mathcal{R}} \mathcal{Q}_{ij}^{k'r} = \mathcal{X}_{ij}^{k'} \qquad \forall i,j \in M', k' \in K_2 \tag{42}$$

$$\widetilde{ed}_i \leq \mathcal{AT}_{ik'} \leq \widetilde{ld}_i \qquad \forall i \in M, k' \in K_2 \tag{43}$$

The time of arrival at the customer, which is equal to the time of readiness of the product for delivery after the accomplishment of the whole required activities plus the movement time of a vehicle between cross dock and customer, is calculated through Eq. (4). Duration of delivery of product to the customer by the vehicle is calculated by constraint (41). Each vehicle, in order to perform transportation among delivery nodes, can select only one speed level, which is determined by constraint (42). Also, fuzzy time windows constraints, which are applied to the arrival time of the vehicle at delivery nodes, are considered in constraint (43).

$$\mathcal{X}_{ij}^{k}, \mathcal{X}_{ij}^{k'}, \mathcal{Y}_{lg}^{p}, \mathcal{Z}_q, \mathcal{W}_u, \mathcal{Q}_{ij}^{kr}, \mathcal{Q}_{ij}^{k'r} \in \{0,1\} \tag{44}$$

$$\mathcal{AT}_{ik}, \mathcal{AT}_{ik'}, \mathcal{ATC}_k, \mathcal{H}_{ij}, \mathcal{E}_u^1, \mathcal{E}_u^2, \mathcal{CT}_{gp}, \mathcal{RT}_p \geq 0 \tag{45}$$

Constraints (44) and (45) represent types of decision variables. Also, $\max_{\mathrm{p}} \mathcal{RT}_{\mathrm{p}}\ell_{\mathrm{ip}}$ is a nonlinear term in constraint (40), which can be converted to a linear term by utilizing Eq. (46).

$$\max_{p} \mathcal{RT}_p \ell_{ip} = \mathcal{Q} \tag{46}$$

Therefore, we can replace constraint (40) with inequality (47):

$$-\mathcal{AT}_{jk'} + \mathcal{Q} + \left(\sum_{r\in\mathcal{R}} d_{0j} \mathcal{Q}_{0j}^{k'r} / \overline{v}^{r}\right) \le \left(1 - \mathcal{X}_{0j}^{k'}\right) \cdot \mathcal{M} \qquad \forall j \in M', k' \in K_2 \tag{47}$$

In addition, constraint (48) is added to the pervious constraints:

$$\mathcal{RT}_p \ell_{ip} \le \mathcal{Q} \quad \forall i \in M, p \in P \tag{48}$$

E. Fuzzy possibilistic programming

To present a corresponding auxiliary crisp model, a fuzzy possibilistic approach, which was proposed by Pishvaee and Torabi (2010), is utilized. Considering the following membership triangular fuzzy number $\tilde{c}$:

$$\mu_{\tilde{c}}(x) = \begin{cases} f_c(x) = \frac{x - c^p}{c^m - c^p} & \text{if } c^p \le x \le c^m \\ 1 & \text{if } \ x = c^m \\ g_c(x) = \frac{c^o - x}{c^o - c^m} & \text{if } c^m \le x \le c^o \\ 0 & \text{if } \ x \le c^p \text{ or } x \ge c^o \end{cases} \tag{49}$$

The fuzzy possiblistic programing approach to a mathematical model, in which the whole parameters are considered as fuzzy number, is as follows:

$min \ \ z = \tilde{c}^t x$

subject to:

$\tilde{a}_i x \ge \tilde{b}_i, i = 1, \dots, l$

$\tilde{a}_i x = \tilde{b}_i, \ i = l + 1, \dots, m$

$$x \ge 0 \tag{50}$$

By utilizing the defuzzification approach, which was proposed by Jimenez et al. (2007), the equivalent crisp α −parametric model is as follows:

$min \ \ z = EV(\tilde{c})x$

subject to:

$\left[(1-\alpha)E_2^{a_i} + \alpha E_1^{a_i}\right]x \ge \alpha E_2^{b_i} + (1-\alpha)E_1^{b_i}, \ i = 1,2 \dots, l$

$\left[\left(1 - \frac{\alpha}{2}\right)E_2^{a_i} + \frac{\alpha}{2}E_1^{a_i}\right]x \ge \frac{\alpha}{2}E_2^{b_i} + \left(1 - \frac{\alpha}{2}\right)E_1^{b_i}, \ i = l + 1, \dots, m$

$\left[\frac{\alpha}{2}E_2^{a_i} + \left(1 - \frac{\alpha}{2}\right)E_1^{a_i}\right]x \le \left(1 - \frac{\alpha}{2}\right)E_2^{b_i} + \frac{\alpha}{2}E_1^{b_i}, \ i = l + 1, \dots, m$

$$x \ge 0. \tag{51}$$

where

$EV(\tilde{c}) = \frac{c^p+2c^m+c^o}{4}$, $E_1^a = \frac{1}{2}(a^p + a^m)$, $E_2^a = \frac{1}{2}(a^m + a^o)$, $E_1^b = \frac{1}{2}(b^p + b^m)$ and $E_2^b = \frac{1}{2}(b^m + b^o)$.

Therefore, by employing this approach, the third objective function and constraints (17) and (43) are converted to a crisp model as follows:

$$Max\ Z_3 = \sum_{i\in N}\sum_{k\in K_1} w_i . e^{\frac{\mathcal{AT}_{ik} - \left(\frac{ep_i^p + 2ep_i^m + ep_i^o}{4}\right)}{\left(\frac{lp_i^p + 2lp_i^m + lp_i^o}{4}\right) - \left(\frac{ep_i^p + 2ep_i^m + ep_i^o}{4}\right)}} + \sum_{i\in M}\sum_{k'\in K_2} w_i' . e^{\frac{\mathcal{AT}_{ik'} - \left(\frac{ed_i^p + 2ed_i^m + ed_i^o}{4}\right)}{\left(\frac{ld_i^p + 2ld_i^m + ld_i^o}{4}\right) - \left(\frac{ed_i^p + 2ed_i^m + ed_i^o}{4}\right)}} \tag{52}$$

$$\left[(1-\alpha)\left(\frac{ep_i^p + ep_i^m}{2}\right) + \alpha\left(\frac{ep_i^p + ep_i^m}{2}\right)\right] \le \mathcal{AT}_{ik} \le \left[\alpha\left(\frac{lp_i^p + lp_i^m}{2}\right) + (1-\alpha)\left(\frac{lp_i^o + lp_i^m}{2}\right)\right] \ \forall i \in N, k \in K_1 \tag{53}$$

$$\left[(1-\alpha)\left(\frac{ep_i^p + ep_i^m}{2}\right) + \alpha\left(\frac{ep_i^p + ep_i^m}{2}\right)\right] \le \mathcal{AT}_{ik} \le \left[\alpha\left(\frac{lp_i^p + lp_i^m}{2}\right) + (1-\alpha)\left(\frac{lp_i^o + lp_i^m}{2}\right)\right] \ \forall i \in N, k \in K_1 \tag{54}$$

III. SOLUTION METHOD

Since the proposed model is NP-hard, obtaining a solution to it in a reasonable time for medium- and large-size problems by employing the commercial software is not possible (Zandieh et al., 2009). Therefore, MOICA and MOGWO are utilized. MOIC has been chosen for the following reasons: 1) suitable rate of convergence, 2) adaptability to different optimization models, 3) powerful neighborhood exploration mechanism, and 4) great global exploration (Hosseini and Al Khaled, 2014). Moreover, the benefits of MOGWO are robustness, pliability, simplicity, and adaptability (Chaleshtari et al., 2017).

A. MOGWO

Mirjalili et al. (2016) offered MOGWO algorithm. With the intention of forming a social hierarchy of wolves, a suitable solution with appropriate fitness is considered as wolf (α). Then, two other solutions, which are called (β) and (δ), are factored in; the remaining of the solutions are called (ω). Afterwards, during the search in the solution space, ω wolves follow these solutions. Subsequently, with the intention of pretending the encircling mechanism of grey wolves, the following relations are applied in order to conduct social leadership (Mirjalili et al., 2014).

$$\vec{D} = \left|\vec{C}.\vec{X}_p(t) - \vec{X}(t)\right| \tag{55}$$

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A}.\vec{D} \tag{56}$$

In these equations, t represents the current iteration, $\vec{X}_p$ is the position vector of the prey, and coefficients vectors are represented by $\vec{A}$ and $\vec{C}$. Also, a grey wolf' position vector is denoted by $\vec{X}$. The following equations are employed to obtain the vectors of coefficients.

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a} \tag{57}$$

$$\vec{C} = 2\vec{r}_2 \tag{58}$$

The random vectors in [0,1] are indicated by $\vec{r}_1$ and $\vec{r}_2$ in these equations. Also, during the development of iterations, the components of $\vec{a}$ are linearly reduced from 2 to 0. In order to conduct hunting, the following equations are employed.

$$\vec{D}_\alpha = \left|\vec{C}_1.\vec{X}_\alpha - \vec{X}\right|,\ \vec{D}_\beta = \left|\vec{C}_2.\vec{X}_\beta - \vec{X}\right|, \vec{D}_\delta = \left|\vec{C}_3.\vec{X}_\delta - \vec{X}\right| \tag{58}$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1.\left(\vec{D}_\alpha\right), \vec{X}_2 = \vec{X}_\beta - \vec{A}_2.\left(\vec{D}_\beta\right), \vec{X}_3 = \vec{X}_\delta - \vec{A}_3.\left(\vec{D}_\delta\right) \tag{59}$$

$$\vec{X}(t+1) = \frac{\vec{X}_1+\vec{X}_2+\vec{X}_3}{3} \tag{60}$$

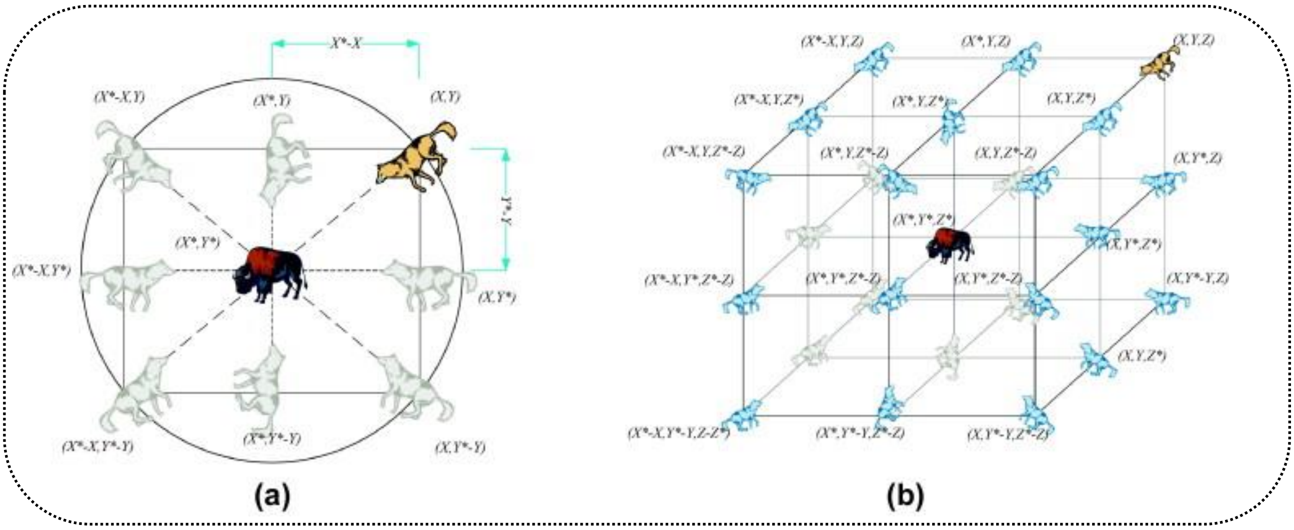
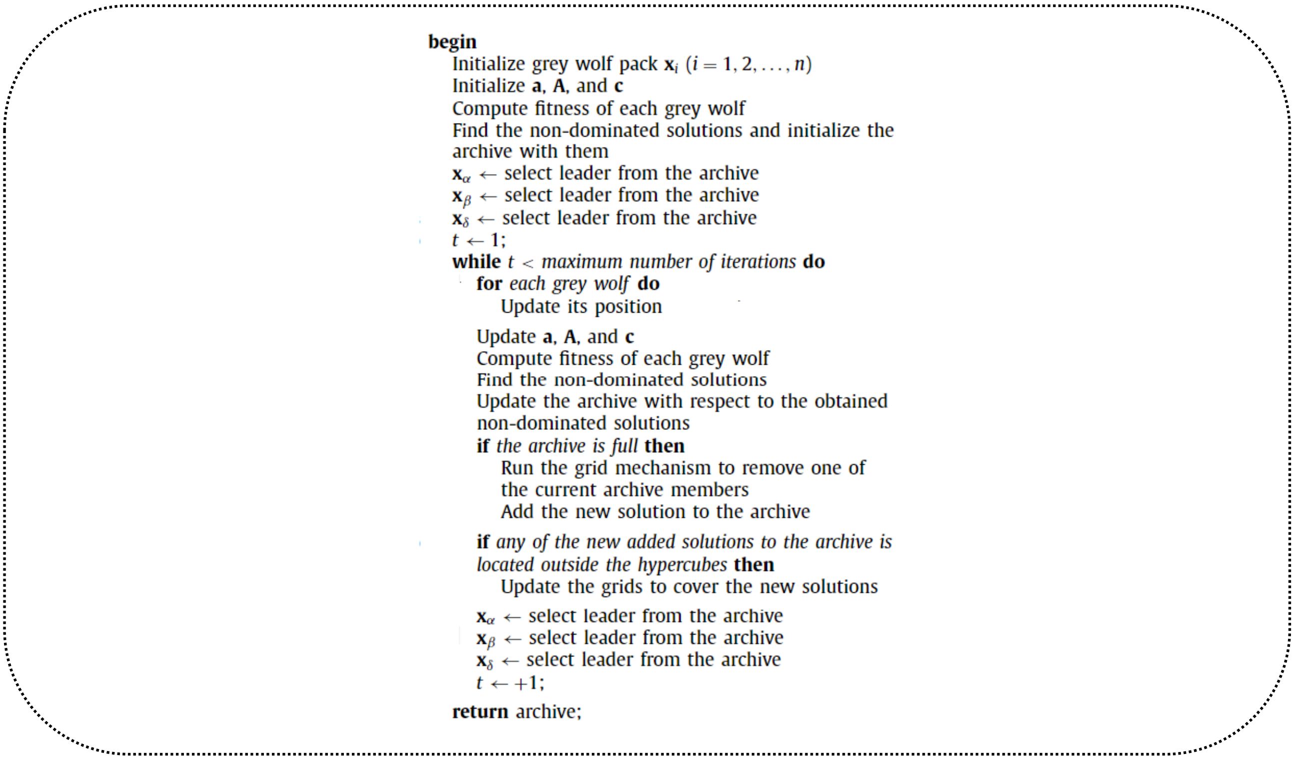


Figure 1. 2D and 3D position vectors and their possible neighbors (Mirjalili et al., 2014)



```
begin
  Initialize grey wolf pack $\mathbf{x}_i$ $(i = 1, 2, \ldots, n)$
  Initialize a, A, and c
  Compute fitness of each grey wolf
  Find the non-dominated solutions and initialize the
  archive with them
  $\mathbf{x}_\alpha \leftarrow$ select leader from the archive
  $\mathbf{x}_\beta \leftarrow$ select leader from the archive
  $\mathbf{x}_\delta \leftarrow$ select leader from the archive
  $t \leftarrow 1$;
  while $t <$ maximum number of iterations do
    for each grey wolf do
      Update its position

    Update a, A, and c
    Compute fitness of each grey wolf
    Find the non-dominated solutions
    Update the archive with respect to the obtained
    non-dominated solutions
    if the archive is full then
      Run the grid mechanism to remove one of
      the current archive members
      Add the new solution to the archive

    if any of the new added solutions to the archive is
    located outside the hypercubes then
      Update the grids to cover the new solutions

    $\mathbf{x}_\alpha \leftarrow$ select leader from the archive
    $\mathbf{x}_\beta \leftarrow$ select leader from the archive
    $\mathbf{x}_\delta \leftarrow$ select leader from the archive
    $t \leftarrow +1$;
  return archive;
```

Figure 2. Pseudo-code of the MOGWO algorithm (Mirjalili et al., 2016)

To illustrate the influence of Eqs. (55) and (56), two- and three-dimensional vectors of positions near the potential updated positions are shown in Figs. (1a) and (1b). Also, the pseudo-code of the MOGWO presented by Mirjalili et al. (2016) is shown in Fig. (2).

B. Solution representation

Solution representation has a crucial role in designing and searching solution space by a meta-heuristic algorithm (Vahdani et al., 2017). In this study, two different solutions are considered; the first one is related to vehicle routing and the second one to consolidation and integration processes, which are utilized inside the cross dock (Abad et al., 2018).

a. Routing

A matrix with two rows and identical columns representing the number of suppliers is considered for the pickup process. The numbers in the first row are randomly chosen from 1 to the number of suppliers. They are integers and their duplication is not permissible. In the second row, the numbers are chosen similarly, but from 1 to the number of available vehicles in the pickup process. It should be noted that, this time, repetitive numbers are acceptable if the number of available vehicles is smaller than the number of suppliers, as shown in Fig. (3).

0	4	5	7	0	1	2	6	8	0	9	3	10	0
*	3	3	3	*	4	4	4	4	*	1	1	1	*

Figure 3. Solution structure for routing (Abad et al., 2018)

b. Integration and consolidation

For the integration and consolidation processes, a $(p \times \mathrm{l})$ matrix is considered, which is shown in Fig. (4). We have identical rows representing the number of types of products and identical columns representing the maximum number of activates. The numbers in this matrix are randomly generated from 1 to the number of administrative agents. The numbers of integration and consolidation are equal to the identical successive numbers observed in the rows and columns, respectively.

	Activities					
Products	***1***	***2***	***3***	***4***	***5***	***Integrations***
1	3	2	2	2	4	1
2	3	1	3	2	2	1
3	4	1	1	3	1	1
4	2	4	1	1	2	1
5	4	4	2	2	3	2
6	4	3	4	4	2	1
Consolidations	2	2	1	1	0	

Figure 4. Solution structure for integration and consolidation (Abad et al., 2018)

C. Performance measures

In this study, 5 predominant metrics are considered in order to assess the performance of the presented multi-objective meta-heuristic algorithms, which are defined as follows:

a. Number of Pareto Solutions (NPS)

The first one is NPS, which demonstrates the number of Pareto optimal solutions.

b. Spacing (S)

The second one is spacing, which explains the extent of spread of the obtained solutions. It is calculated as follows (Schott, 1995):

$$S = \sqrt{\frac{1}{|n|}\sum_{i=1}^{n}\left(d_i - \bar{d}\right)^2} \tag{61}$$

where $d_i = \min_{k \in n \wedge k \neq 1}\left\{\sum_m \left|f_m^i - f_m^k\right|\right\}, \bar{d} = \sum_{i=1}^{n}\frac{d_i}{|n|}$ and n specifies the size of the Pareto front. Smaller values of this metric are desired.

c. Maximum Spread (MS)

The third one is maximum spread or diversity, which is calculated as follows (Zitzler, 1999):

$$MS = \sqrt{\sum_{m=1}^{M}\left(max_{i=1}^{|N|} f_m^i - min_{i=1}^{|N|} f_m^i\right)} \tag{62}$$

Higher MS is favorable.

d. Set coverage metric

The fourth one is set coverage metric, which is employed for conflicting sets of non-dominated solutions. It is calculated as follows (Zitzler and Thiele, 998):

$$C(A,B) = \frac{|\{b \in B | \exists a \in A : a \succ b\}|}{|B|} \tag{63}$$

$$Q(A,B) = \frac{C(A,B)}{C(A,B) + C(B,A)} \tag{64}$$

e. Non-uniformity of Pareto Front (NPF)

The fifth one is NPF, which is employed to assess the non-uniformity of the spreading of a Pareto curve. It is computed as follows (Deb, 2001):

$$NPF = \sqrt{\frac{\sum_i\left(\frac{d_i}{\bar{d}} - 1\right)^2}{|A| - 1}} \tag{65}$$

where $d_i = \min_{k \in n \wedge k \neq 1}\left\{\sum_m \left|f_m^i - f_m^k\right|\right\}, \bar{d} = \sum_{i=1}^{A}\frac{d_i}{|A|}$. Lower values of this metric are desired.

IV. COMPUTATIONAL RESULTS

A. Numerical results

In this section, with the intention of demonstrating the accuracy of the presented model and solution approach, 30 test problems are sketched out. The values of the input parameters are shown in Table III. Also, in order to show validity of the presented model, a small test problem is solved by GAMS software; the obtained solution is graphically illustrated in Fig. (5). Since the presented model is multi-objective, LP metric method is utilized in order to convert this model to a single-objective one. Furthermore, the obtained results from 5 performance metrics for 30 test problems are provided in Tables IV and V, and Figs. (6) to (10). Also, for better comparison of these algorithms, Figs. (11) to (15) illustrated the box plots of these metrics. The obtained results reveal that MOGWO has better performance than a multi-objective imperialist competitive algorithm in some criteria . As depicted in Fig. (5), supply of the first product is conducted by suppliers 1, 3 ,5, and 9. The first vehicle is employed for the pickup process from suppliers 3 and 9, and the second vehicle is utilized for suppliers 1 and 5. Moreover, the pickup process for supplier 3 is completed by utilizing the first and second vehicles; in fact, the split pickup occurs for this supplier. As we can see, the first and second activities on the first product are integrated. Similarly, the first to third activities on the second product are also integrated. Furthermore, the fourth activity on the first and second products is consolidated. The picked up and delivered products among suppliers and customers are shown in this figure.

Table III. Sources of parameters for test problems

Parameter	***Value***	***Parameter***	***Value***
$\mathcal{v}_{ip}$	~ uniform(5,50)	$\mathcal{p}t_i, dt_i$	~ uniform(4,12)
$\mathcal{D}_{ip}$	~ uniform(5,50)	$\widetilde{e\mathcal{p}}_i, \widetilde{ed}_i$	$e\mathcal{p}_i^m, ed_i^m$ ~ uniform(8,13)
α_p, γ_p	~ uniform(0.5,1.5)	$\widetilde{l\mathcal{p}}_i, \widetilde{ld}_i$	$l\mathcal{p}_i^m, ld_i^m$ ~ uniform(14,24)
$\mathcal{C}$	~ uniform(140,250)	d_{ij}	~ uniform(25,80)
t_{lpb}	~ uniform(60,300)	$\overline{v}^r$	~ uniform(25,75)
$c_{ij}^k, c_{ij}^{k'}$	~ uniform(50,300)	ζ_n	~ uniform(20,45)
$st_{q,g}^{int}$	~ uniform(120,200)	scs_q^{int}	~ uniform(35,60)
$\mathcal{S}_{lg}^p$	~ uniform(50,110)	cs_u^{con}	~ uniform(45,75)
$\mathcal{P}_{lg}^p$	~ uniform(10,30)		

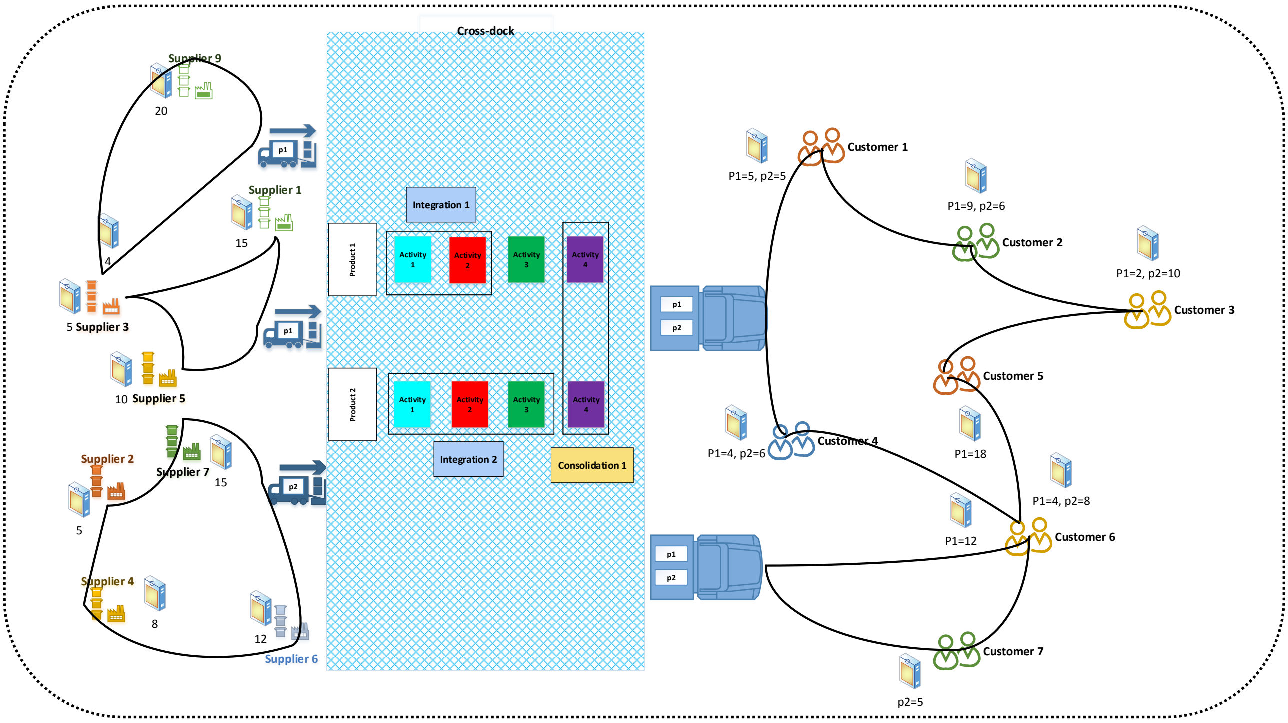


Figure 5. A graphic solution

Table IV. Results of criteria for MOICA

	Structure	***Performance measure***				
Problem No.	$N/M/K_1/K_2/P/A/B/\mathfrak{R}$	NPS	S	MS	Q	NPF
1	7/7/3/3/2/4/4/2	41	0.35	44	0.07	0.35
2	10/10/5/5/3/4/4/2	26	0.33	33	0.03	0.31
3	14/14/7/7/4/5/5/2	23	0.11	22	0.00	0.05
4	16/16/7/7/5/5/5/3	34	0.36	47	0.00	0.30
5	18/18/7/7/6/5/5/3	37	0.80	48	0.04	0.57
6	20/20/8/8/6/6/5/3	33	0.60	33	0.22	0.52
7	25/25/8/8/6/6/5/3	29	0.98	40	0.30	1.12
8	30/30/9/9/6/6/5/3	33	0.06	36	0.20	0.09
9	35/35/9/9/6/6/6/3	34	0.31	36	0.11	0.27
10	40/40/9/9/6/6/6/3	38	0.49	50	0.28	0.44
11	45/45/10/10/6/6/6/3	29	0.19	33	0.02	0.19
12	50/50/10/10/6/7/6/4	31	0.13	34	0.19	0.02
13	52/52/12/12/6/7/6/3	39	0.55	44	0.10	0.47
14	50/54/13/14/7/7/6/3	29	0.33	33	0.06	0.15
15	54/50/12/15/8/7/6/3	37	0.26	35	0.01	0.04
16	54/51/13/15/9/8/8/3	38	1.37	53	0.03	0.43
17	52/54/12/16/8/8/6/3	31	0.53	34	0.11	0.27
18	54/54/11/10/7/7/7/3	36	0.22	39	0.38	0.21
19	53/53/12/11/7/9/8/4	31	0.39	48	0.07	1.15
20	54/53/12/11/7/7/8/4	39	0.81	44	0.00	0.51
21	55/55/12/11/8/9/8/4	40	0.70	46	0.05	0.28
22	55/55/12/12/6/6/6/4	30	1.05	37	0.26	0.33
23	55/55/13/12/7/7/6/4	27	0.61	43	0.57	0.59
24	55/55/14/14/7/7/6/4	34	1.10	53	0.07	0.75
25	55/55/16/16/7/7/7/4	38	0.31	56	0.33	0.63
26	60/60/17/17/7/7/7/4	40	0.89	48	0.26	0.80
27	65/65/18/18/7/7/7/4	38	0.98	39	0.09	0.22
28	68/68/19/19/8/7/7/4	33	1.16	46	0.15	0.99
29	70/70/20/20/8/7/7/4	35	0.12	45	0.06	0.73
30	75/75/20/20/8/8/7/4	30	0.41	41	0.26	0.18
Ave		33.77	0.55	41.33	0.14	0.43

$St.dev.$		4.65	0.36	7.65	0.14	0.31

Table V. Results of criteria for MOGWO

	Structure	***Performance measure***				
Problem No.	$N/M/K_1/K_2/P/A/B/\mathcal{R}$	NPS	S	MS	Q	NPF
1	55/55/13/12/7/7/6/4	40	0.51	60	0.92	0.37
2	55/55/13/12/7/7/6/4	36	0.93	57	1.00	0.65
3	55/55/13/12/7/7/6/4	37	0.52	55	0.89	0.41
4	55/55/13/12/7/7/6/4	39	0.56	66	1.00	0.44
5	55/55/13/12/7/7/6/4	38	0.81	60	1.00	0.55
6	55/55/13/12/7/7/6/4	37	1.09	69	0.75	0.71
7	55/55/13/12/7/7/6/4	36	0.79	53	0.66	0.65
8	55/55/13/12/7/7/6/4	38	0.60	56	0.80	0.47
9	55/55/13/12/7/7/6/4	36	1.12	67	0.93	0.64
10	55/55/13/12/7/7/6/4	35	0.77	61	0.74	0.59
11	55/55/13/12/7/7/6/4	37	1.19	58	1.00	0.68
12	55/55/13/12/7/7/6/4	38	0.48	61	0.74	0.56
13	55/55/13/12/7/7/6/4	39	0.69	59	0.91	0.79
14	55/55/13/12/7/7/6/4	40	0.85	64	0.89	0.42
15	55/55/13/12/7/7/6/4	38	0.77	58	1.00	0.52
16	55/55/13/12/7/7/6/4	41	0.55	69	0.07	0.60
17	55/55/13/12/7/7/6/4	37	0.90	60	0.91	0.48
18	55/55/13/12/7/7/6/4	36	1.06	56	0.69	0.59
19	55/55/13/12/7/7/6/4	39	0.62	64	1.00	0.66
20	55/55/13/12/7/7/6/4	37	0.96	69	0.67	0.60
21	55/55/13/12/7/7/6/4	36	1.15	75	0.71	0.41
22	55/55/13/12/7/7/6/4	40	0.78	73	0.50	0.59
23	55/55/13/12/7/7/6/4	36	0.87	66	0.87	0.64
24	55/55/13/12/7/7/6/4	38	0.91	71	0.77	0.51
25	55/55/13/12/7/7/6/4	42	1.02	78	0.84	0.52
26	55/55/13/12/7/7/6/4	40	0.65	69	0.98	0.68
27	55/55/13/12/7/7/6/4	39	0.77	75	0.47	0.77
28	55/55/13/12/7/7/6/4	41	0.70	65	0.69	0.45
29	55/55/13/12/7/7/6/4	35	0.81	80	0.75	0.53
30	55/55/13/12/7/7/6/4	43	0.99	66	0.59	0.67
Ave		38.13	0.81	64.67	0.79	0.57

$St.dev.$		2.08	0.20	7.13	0.20	0.11

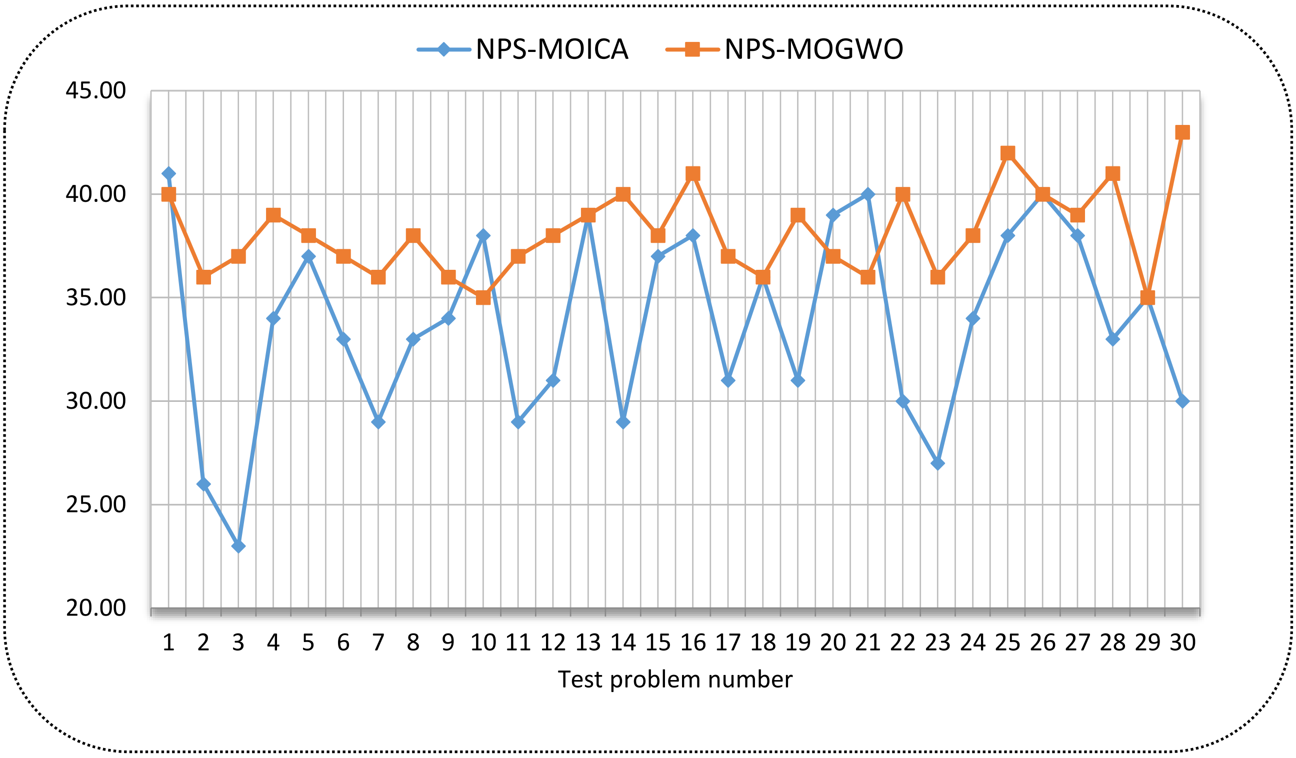


Figure 6. Graphical comparison of the algorithms for the criterion NPS

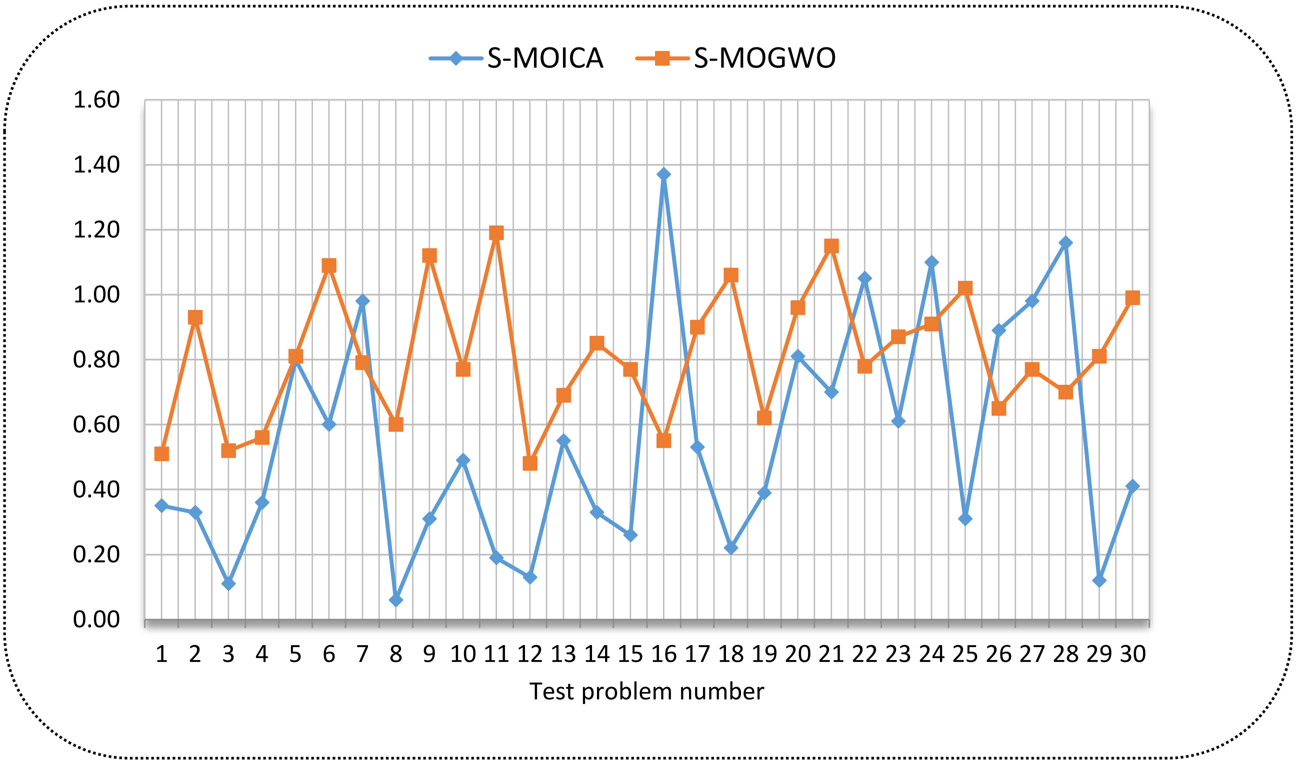


Figure 7. Graphical comparison of the algorithms for the criterion *S*

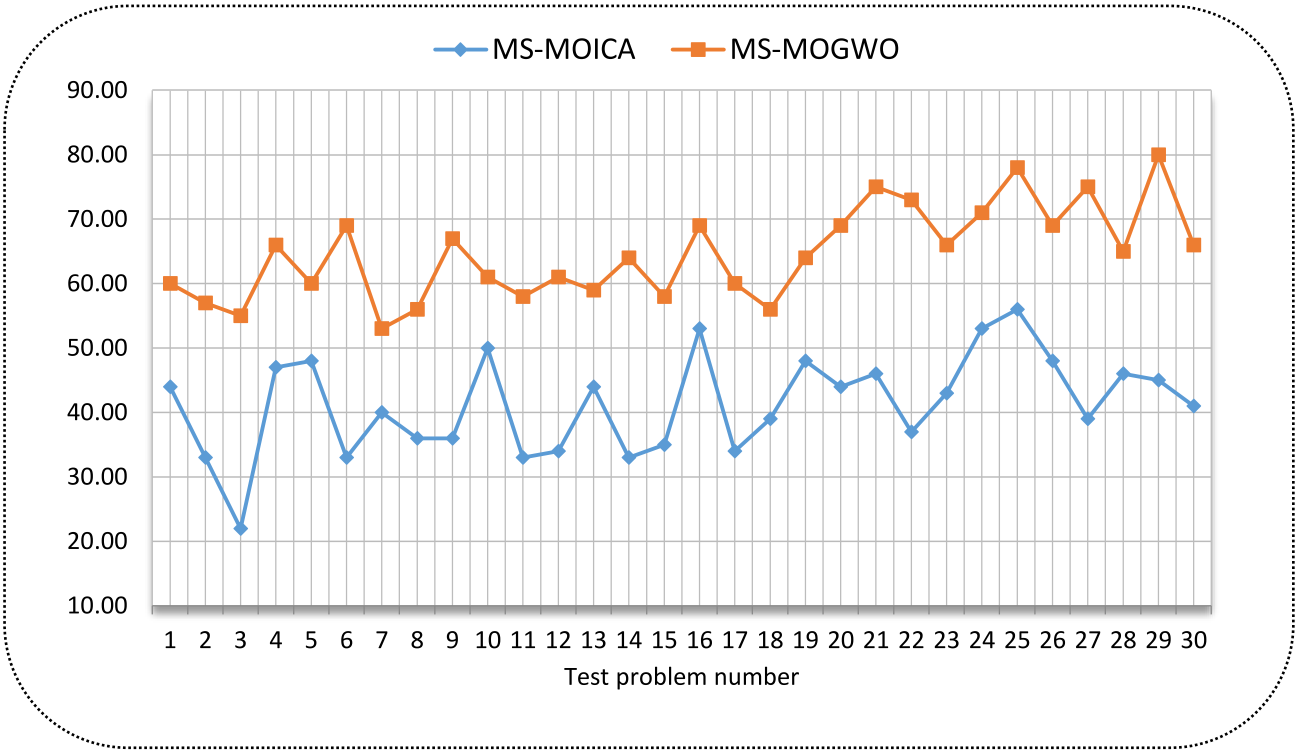


Figure 8. Graphical comparison of the algorithms for the criterion *MS*

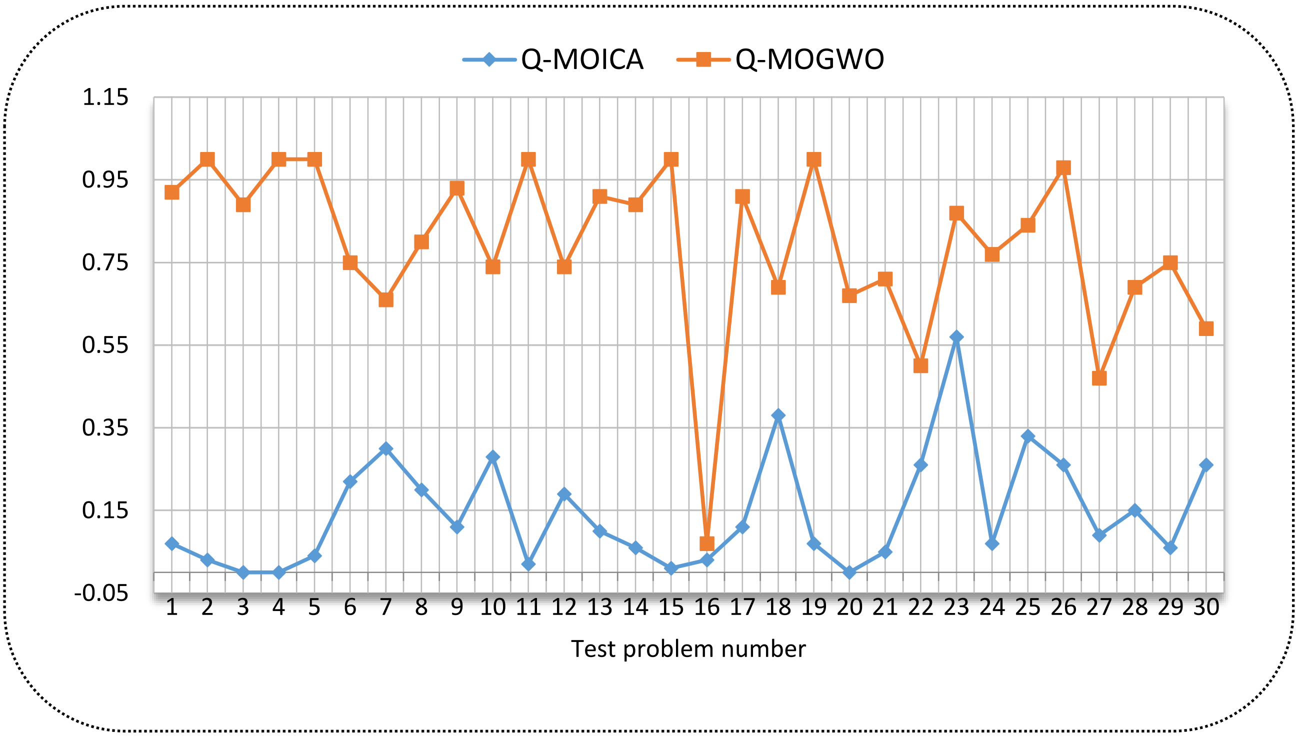


Figure 9. Graphical comparison of the algorithms for the criterion *Q*

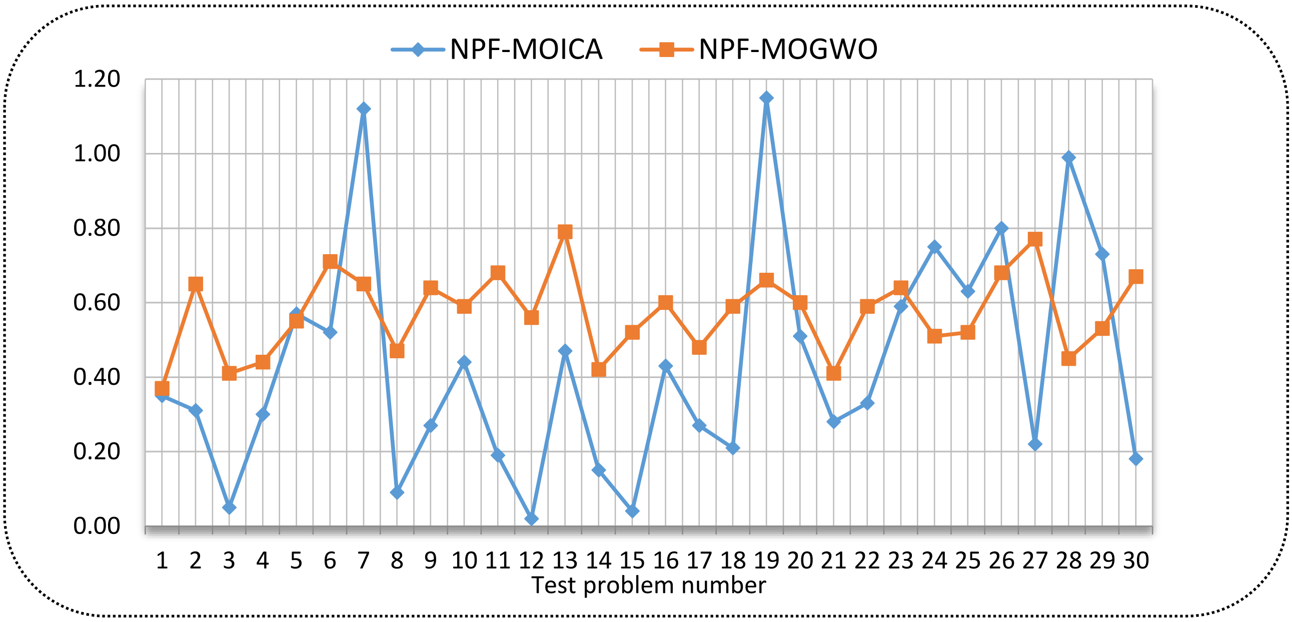
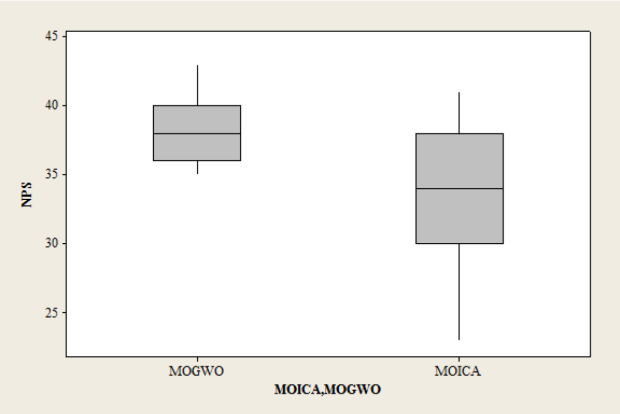


Figure 10. Graphical comparison of the algorithms for the criterion *NPF*



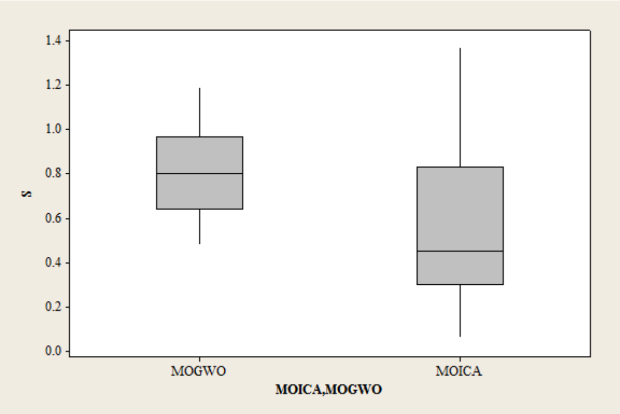
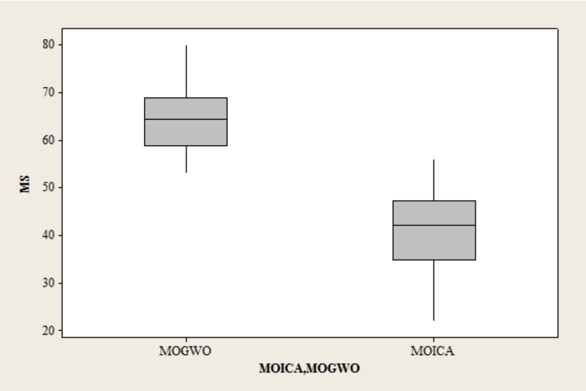


Figure 11. Box plot of the metric *NPS* **Figure 12. Box plot of the metric *S***



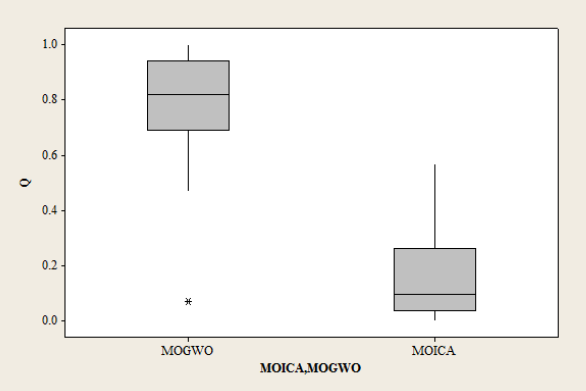


Figure 13. Box plot of the metric *MS*

Figure 14. Box plot of the metric *Q*

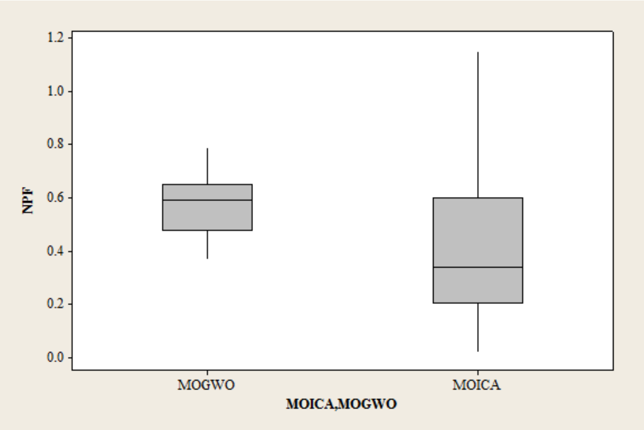


Figure 15. Box plot of the metric *NPF*

B. Sensitivity analysis

In order to study the effect of the parameters of the model on the obtained results, sensitivity analysis is conducted and the results are presented in Figs. (16) and (17). Fig. (16) shows the impact of demand on average satisfaction degrees. To illustrate this trend, the capacities of vehicles are considered to be fixed. As can be seen, with increase in demand, in the case of split pickup and delivery, the average satisfaction degrees of customers and suppliers are enhanced. The reason in that with increase in demand, it may not be possible to meet the total demand of customers by using only one vehicle in a short time, but with split pickup and delivery, this is possible.

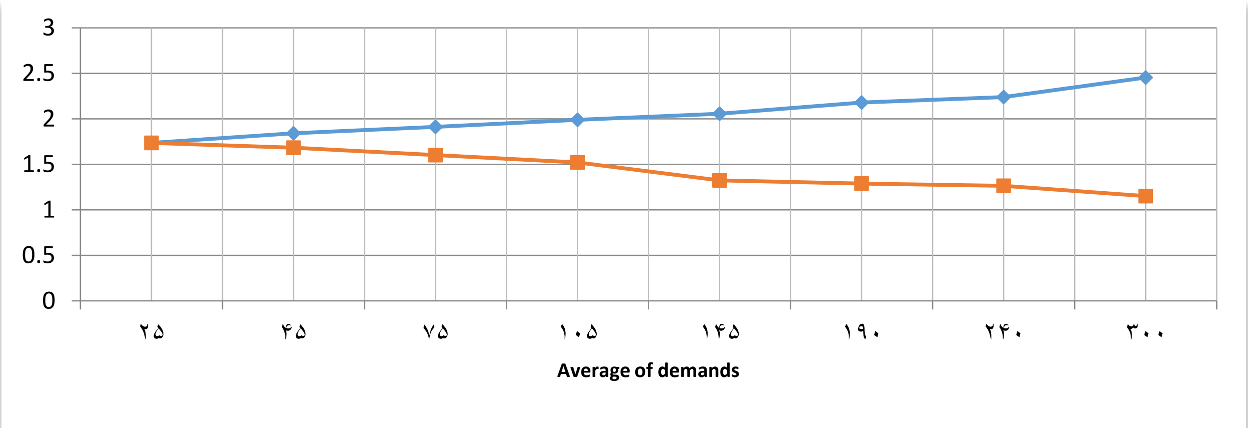


Figure 16. Impact of demand on satisfaction degree

Fig. (16) shows the impact of consolidation and integration on total arrival times. As can be seen, by considering these processes, the total arrival time for delivery of products increases. Although consideration of activities inside cross dock leads to increase in time of delivery of products to customers, the planning of the cross docking system will be more accurate.

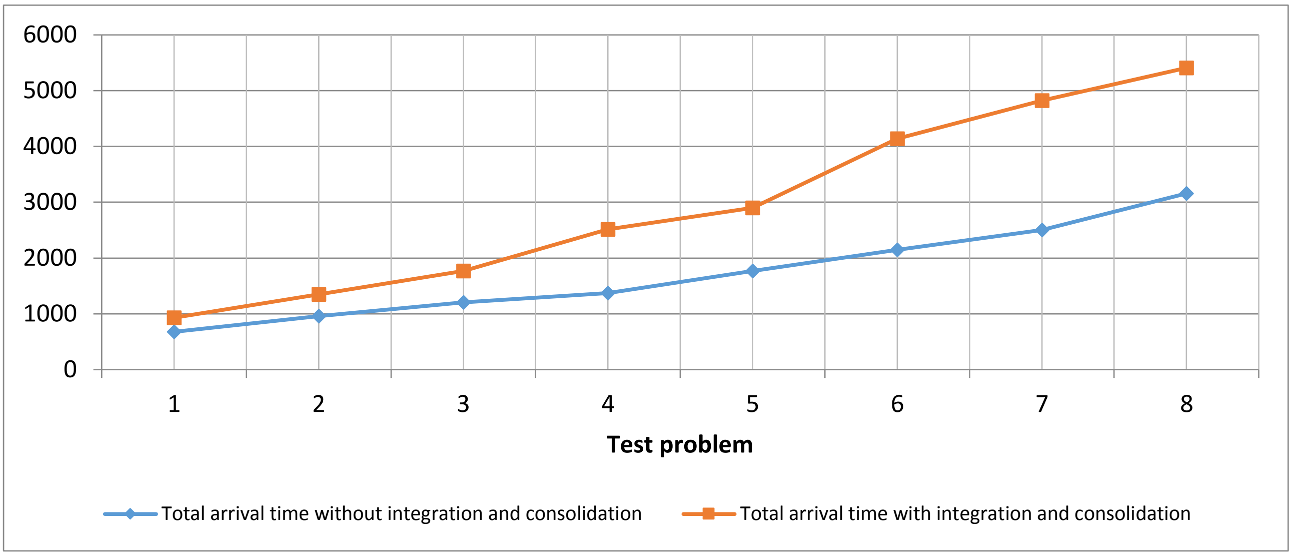


Figure 17. Total arrival time with and without integration and consolidation

V. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

A multi-objective mathematical model was presented, which had 3 objective functions, including costs for the cross-docking system, the fuel consumption of vehicles, and satisfaction degrees. In this study, a broad range of activities, including outdoor and indoor, were considered in order to develop a comprehensive framework for planning a cross-docking system. Indoor activities included consolidation and integration, and outdoor activities included vehicle routing and scheduling problem. It should be noted that in order to present a realistic model, split delivery and pickup concept were considered. Moreover, due to the uncertainty in predicting the preferable time windows of suppliers and customers, a fuzzy possibilistic programming approach was adopted. Since the proposed model was NP-hard and multi-objective, 2 multi-objective meta-heuristic algorithms, namely MOICA and MOGWO, were utilized. Furthermore, to show validity of the proposed model and solution approaches, different numerical examples were presented. The obtained results revealed that multi-objective grey wolf optimizer had better performance than a multi-objective imperialist competitive algorithm in some criteria. Furthermore, sensitivity analysis illustrated effectiveness of considering the split concept in pickup and delivery processes. There are some possible future directions such as considering capacity for executive agents, sharing available resources between agents, and improving solution approaches.

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