

A Genetic Algorithm with Multiple Populations to Reduce Fuel Consumption in Supply Chain

Mohammad Ali Beheshtinia^{*1}, Bahar Ahmadi², Masood Fathi³

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Abstract

Reducing fuel consumption by transportation fleet in a supply chain, reduces transportation costs and consequently, the product final cost. Moreover, it reduces environmental pollution, and in some cases, it helps governments constitute less subsidies for fuels. In this paper, a supply chain scheduling is studied, with the two objective functions of minimizing the total fuel consumption, and the total order delivery time. After presenting the mathematical model of the problem, a genetic algorithm, named Social Genetic Algorithm (SGA) is proposed to solve it. The proposed algorithm helps decision makers determine the allocation of orders to the suppliers and vehicles and production and transportation scheduling to minimize total order delivery time and fuel consumption. In order for SGA performance evaluation, its results are compared with another genetic algorithm in the literature and optimal solution. Finally, a sensitivity analysis is performed on SGA. The results of comparisons also show the high performance of SGA. Moreover, by increasing the number of suppliers and vehicles and decreasing the number of orders, the value of the objective function is reduced.

Keywords: Transportation, fuel consumption, supply chain management, routing, genetic algorithm.

Corresponding author E-mail: beheshtinia@semnan.ac.ir

1 Associate Professor, Industrial Engineering Department, Semnan University, Semnan, Iran

2 MSc. Grad., Department of Industrial Engineering, , Semnan University, Semnan, Iran

3 Assistant Professor, Department of Production and Automation Engineering, University of Skövde, Skövde, Sweden

1. Introduction

Due to the increase in competitiveness in the current business environment, one of the main concerns of manufacturers is reducing the final product cost. Reducing transportation costs have a major role in reducing the final product cost. Also, it reduces environmental pollution, and in some cases, it helps governments constitute less subsidies for fuels. Therefore, this is an interesting matter from micro-economic, macro-economic and environment pollution aspects.

A supply chain includes all the steps that create a value-added product. Supply chain management may be defined as the integration of organizational units and the coordination of material flows and financial information throughout the supply chain in order to satisfy (final) customer demand with the aim of improving the competitiveness of a supply chain. In this study, the fuel consumption of transportation fleet in a supply chain is reduced by optimization of vehicles routing. Vehicles routing directly affects production and transportation scheduling and subsequently order delivery times. Separate decisions without considering this interaction do not guarantee an optimal solution. For example, suppose the processed orders by suppliers are waited and stocked and conveyed to the manufacturer by a cargo. It reduces transportation cost but causes higher order delivery time.

The paper examines the scheduling problem in a three-stage supply chain, considering the integrations between the stages. The first stage includes the suppliers, the second stage includes goods transportation fleet, and the third stage is the manufacturer of finished products.

In integrated systems, the relationship between the schedule of orders in production stage, and their schedule and allocation to suppliers is one of the most important areas, studied by many researchers. The traditional methods consider the scheduling at the production and supplier stages,

separately; and do not consider the interplay between these two.

In the remainder of this paper, Section 2 reviews the related literature. Assumptions of the problem and the proposed mathematical model are presented in Section 3. The proposed algorithm, used for solving the problem is provided in Section 4. In Section 5, the numerical experiments and results are discussed. Eventually, conclusion and future research scopes are presented in Section 6.

2. Literature Review

Several researches have been conducted on scheduling in supply chain. [Zhou et al. 2000] studied the optimization of the supply chain in continuous process industries with sustainability considerations. Sustainability involves multiple objectives such as social, economic, resource, and environmental sustainability, some of which are in conflict with others. They have modeled a case study using the above restrictions. [Lee et al. 2002] studied advanced planning and scheduling in manufacturing supply chain. They assumed that each order has a delivery date. Products that must be finished in each order, must be processed in the assembly stages in an order. There might be priority constraints for completing the jobs. [Gnoni et al. 2003] studied production planning in multi-site manufacturing systems. In their study, it is assumed there are probabilistic demands for some semi-finished parts. To solve the problem, they used a combination of mathematical mixed-integer programming models and simulation and benefited from the advantages of both of these models in dealing with this issue.

[Chang and Lee, 2004] studied the machine scheduling in supply chain. Their supply chain problem includes two phases. The first phase is the production phase and the second

A Genetic Algorithm with Multiple Populations to Reduce Fuel Consumption in Supply Chain

phase is the transportation and delivery of goods to customers. The objective function is to minimize the completion times of jobs. In this problem, the production phase may include one or more machines. Also, customers may exist in one region or in different regions. Each vehicle has a capacity limit that is related to the space in which jobs can be carried in a single trip. Each job may occupy a different amount of space than the other. A transportation time is also considered for each delivery of goods. The objective function is to minimize the total completion time for all jobs. They have examined simple cases of the problem where only one vehicle constitutes the transportation fleet and a heuristic was offered for each of them.

[Chan et al. 2005] studied distributed scheduling problems in a multi-product and multi-factory environment. The purpose was to allocate jobs to different factories and to determine production scheduling for all factories. An adaptive genetic algorithm with a new crossover operator named “dominated gene” was provided to solve the problem. [Lejeune, 2006] studied production and distribution planning in supply chain. After modeling the problem as a mixed-integer programming, an algorithm was presented based on the variable neighborhood search method, which is a step by step process. This research studies production planning and scheduling from a macro perspective and does not consider machinery scheduling. [Selvarajah and Steiner, 2006] studied the batch scheduling in supply chain from the suppliers’ viewpoint. The purpose is to determine the size of product batches for customers and the completion time of each batch of product for the certain customer, so that the total costs of maintenance and order delivery would be minimized. They proposed an algorithm with polynomial complexity for a case of one supplier and several customers. In this study, no attention has been given to suppliers inside the supply chain and only the relationship between manufacturer and customers has been considered. [Chauhan et al. 2007] studied

scheduling in supply chain with the aim of minimizing the maximum completion time of the jobs. They solved the problem for two cases of assembly operations and have presented a heuristic algorithm for each of them. [Li and Womer, 2008] studied the supply chain configuration problem, considering resource constraints. [Zegordi and Beheshti Nia, 2009a] studied the integration of production and transportation scheduling in the supply chain. In their study, transportations have been considered as back and forth processes.

[Scholz-Reiter et al. 2010] studied the integration of manufacturing and logistics systems and have presented a mathematical model to solve the problem. [Yeung et al. 2011] studied scheduling in a two-stage supply chain, considering several common delivery time windows in order to minimize delivery costs. [Bhatnagar et al. 2011] investigated the transportation planning and scheduling in the case of the two air and sea transportation types. The objective function was to minimize the cost of maintaining inventory, the number of used containers and shipping costs. [Mehravaran and Logendran, 2012] studies scheduling in workflow environment with sequencing-dependent preparation times. The two objective functions are to minimize the half-built orders and to maximize service levels. They have offered a liner mathematical model to solve the problem for a case in which the sequence of orders in different stages may vary. A taboo search algorithm was presented for solving the problem. [Osman and Demirli, 2012] studied economic lot and delivery scheduling problem in a multi-product, three-stage supply chain. They suggested a new model based on allocation problem which determines a common cycle for synchronizing the replenishment of warehouses. [Liu and Chen, 2012] examined the routing integration, scheduling, and

inventory control in a supply chain. After mathematically modeling the problem, they suggested a neighborhood search algorithm for solving the problem. The objective function is to minimize the total cost of inventory, routing and use of vehicles.

[Averbakh and Baysan, 2013] studied the on-line multi-customer two-level supply chain scheduling problem and have presented an approximation algorithm to solve it. Minimizing the total order flow and delivery costs has been considered as the objective function. [Ren et al. 2013] examined a two-stage supply chain in which several suppliers provide the needed parts for an assembler. The delivery time of each product equals the maximum delivery time of the parts that suppliers provide for the assembler. [Ullrich, 2013] studied the integration of machine scheduling and vehicle routing with time windows. They examined a two-stage supply chain. The first stage included a parallel machine environment with machine-dependent preparation times and the second stage included a fleet of vehicles with different capacities.

[Thomas et al. 2014] investigated scheduling in a coal supply chain with several independent activities that are related by resource constraints. The problem composed of two planning and scheduling sub-problems. They offered a mixed-integer mathematical model to solve a problem and used the column production technique. [Selvarajah and Zhang, 2014] studied a supply chain scheduling in which a manufacturer receives semi-finished materials from suppliers at different times and delivers finished products to customers in a batch form. The objective function was to minimize weighted total cost of inventory holding and delivery costs. They proposed a heuristic algorithm to solve the problem and provided a lower bound to evaluate the efficiency of the proposed algorithm. [Sawik, 2014] investigated the relationship between the scheduling and the selection of suppliers in case of interruption risks, and presented a mixed-integer programming model for the problem. It was assumed that there were two categories of

suppliers. The first suppliers are within the production region of the main company, and the second suppliers are outside the region. The first category of suppliers inflicts high costs on the system and is certain; while the second category of suppliers is less costly and is uncertain. The objective function is to minimize the costs and increasing service levels. [Pei et al. 2015] tried to solve the production and transportation scheduling problem in a two-stage supply chain in which the process time of each job is a linear function of its starting time. [Ehm and Freitag, 2016] presented a model to integrate production and transportation scheduling, using missed-integer programming method. [Beheshtinia and Ghasemi, 2017] presented a new meta-heuristic named MLCA to solve the integrated production and scheduling problem in supply chain in multi-site manufacturing system. [Beheshtinia et al. 2018] presented a developed version of genetic algorithm named RGGGA to solve the integrated production and scheduling problem in supply chain. [Borumand and Beheshtinia, 2018] used a combination of GA with VIKOR method to solve supply chain scheduling problem. Najian and Beheshtinia [Najian and Beheshtinia, 2018] addressed supply chain scheduling using a combination of cross-docking and VRP approach. [Alinezhad et al. 2018] proposed a variant of Particle Swarm Optimization (PSO) to solve a Vehicle Routing Problem with Time Windows (VRPTW). Moreover, they consider simultaneous delivery and pickup and Capacitated Vehicle Routing Problem (CVRP) as well as Open Vehicle Routing Problem (OVRP). [Sarvestani et al. 2019] introduced a heuristic algorithm for profit maximization in an integrated supplier selection, order acceptance and scheduling problem in a single-machine environment with multiple customers.

A glance at the literature shows that some researches considered single objective

A Genetic Algorithm with Multiple Populations to Reduce Fuel Consumption in Supply Chain

functions and others used multiple objective functions. In another aspect, some researches considered time as a continuous parameter; however, others considered it as discrete time periods. When time is a continuous parameter, the problem is usually NP-Hard. Based on the integration level in the supply chain, the studies may be categorized in 3 levels. Some researches considered the relation between the manufacture and its suppliers, some of them considered the manufacturer and its customers, and others considered both mentioned relations, simultaneously. In terms of transportation, some of studies only considered production scheduling in the supply chain; however, others integrated production and transportation scheduling. In this research, time is considered as a continuous parameter and production and transportation scheduling are integrated to synchronize the manufacturer with its suppliers. Moreover, the two objective functions of minimizing total delivery time and minimizing total fuel consumption by the vehicles are considered in the problem, simultaneously.

In the research performed by [Zegordi and Beheshti Nia, 2009a] each vehicle transports goods in a route between suppliers and the manufacturer. In other words, the distances between suppliers which had the permission to cooperate and participate in transportation of orders were considered to be negligible. Transportation calculations between suppliers were ignored, and there was no routing problem. However, in this paper, the calculations between suppliers are considered and the routing problem is also investigated. Furthermore, this problem considers minimizing of total orders delivery times and total fuel consumption by the vehicles, simultaneously. The contributions of this study to the literature are listed as follows:

- Integration of production and transportation scheduling in the supply chain by taking into account the two objective functions: minimizing fuel

consumption and minimizing the total delivery time of orders

- Adapting a genetic algorithm with multiple populations to solve the problem.

3. Problem Definition

3.1 Research steps

In this paper, the scheduling of a three-stage supply chain is investigated. The first stage consists of suppliers, the second stage is composed of the initial parts transportation fleet, and the third stage is a manufacturer of the finished products. The aim is to minimize total delivery time of orders and total fuel consumption.

Every study seeks to answer some questions. The main question of this study is as follows:

How to minimize fuel consumption and total delivery time in the proposed problem?

Research sub-questions include:

- How to assign each order to an appropriate supplier?
- What are sequence and scheduling of assigned orders to each supplier?
- How are the cargos allocated to the vehicles?
- What routs should the vehicles use to deliver orders?
- How are the vehicles scheduled for delivering orders?

The research steps are as follows:

Step 1: Presenting a mathematical model for the problem

Step 2: Prospering a genetic algorithm named SGA with multiple populations to solve the problem

Step 3: Performing numerical experiments:

Step 3-1: Generating test problems

Step 3-2: Comparing SGA with a single population genetic algorithm

Step 3-3: Comparing the results obtained by SGA and a single population genetic algorithm

Step 3-4: Comparing the results obtained by SGA and the optimum solution

Step 3-5: Performing sensitivity analysis based on the problem's parameters.

3.2 Problem Specification

The assumptions in the problem are as follows:

- There is a manufacturer that must allocate No orders to Ns suppliers.
- Each supplier must produce its allocated orders. Suppliers have different production capacities and some of them may have greater production speed compared to other suppliers, due to having better equipment and machinery and provide the manufacturer's needed items and materials more quickly.
- Processed orders by suppliers should be transported to the manufacturer by Nv vehicles that compose the transportation fleet and have different transportation capacities and speeds.
- The capacity occupied by each product is constant and may be determined based on its volume or weight.
- If the total occupied capacity of assigned orders to a vehicle is more than the capacity of the vehicle, the order must be carried in several batches and the capacity of each batch should not exceed the vehicle's capacity. In other words, after transporting goods from suppliers to manufacturers, vehicles will not be removed and should be used again. In this case, vehicle must be transported

back to where suppliers are located and then be used again.

- Vehicles may carry the parts produced by different suppliers in one cargo. This reduces transportation costs and increases their efficiency.
- Vehicles may also carry parts or materials needed to complete different orders in one cargo.
- Suppliers may have different distances from each other and from the manufacturer.
- The starting point of transportation fleet is the manufacturing company. In fact, the transportation fleet is located inside the manufacturing company.
- If a vehicle with the speed VS travels a distance dis , the travel time is dis/VS . The suppliers' speed can be different from each other. This speed is expressed in terms of machine-hour per time ratio. If the order i with the processing time pt_i is allocated at the supplier s , the real processing time of order i in the supplier stage is calculated through the ratio pt_i/SS_s , in which SS_s is the processing speed of supplier s [Zegordi and Beheshtinia, 2009b].

3.3 Mathematical Model

Before presenting the mathematical model, first the symbols are introduced. The problem parameters

are as follows:

No	Number of orders
Ns	Number of suppliers
Nv	Number of vehicles
q, i	Order index
p	Carrying priority index in each batch (position of order in each batch)
s, s'	Supplier index
m	Vehicle index

A Genetic Algorithm with Multiple Populations to Reduce Fuel Consumption in Supply Chain

b	Batch (mission of vehicles) index
$Size_i$	Occupied capacity by i^{th} order
Cap_m	Capacity of vehicle m (according to the number of orders)
pt_i	Process time of i^{th} order
SS_s	Speed of processing by s^{th} supplier
$disTS_s$ ($disST_s$)	Distance from the factory to the supplier s (from supplier s to the factory)
$disSS_{ss'}$	Distance from supplier s to supplier s'
VS_m	Transportation speed by m^{th} vehicle
$EFMS_m$ ($ESFMS$)	Amount of the fuel consumed, if vehicle m , with its b^{th} batch, travels from the factory to supplier s (supplier s to factory)
$ESS_{mss'}$	Amount of the fuel consumed when vehicle m^{th} travels from supplier s to supplier s'
A	a $No*Ns$ matrix where the allocation of order i to supplier s is allowed, if $a(i,s)$ equals 1; otherwise, the allocation is not allowed
M	A large positive number

In this problem, each vehicle may convey various batches. In other words, it has various missions. In the proposed mathematical model, for each batch (mission) of each vehicle, positions are considered, which show the transportation priority for the orders assigned to the same batch. Because it may be possible that all orders are

assigned to one batch of a vehicle, No positions should be considered. In the proposed mathematical model, a dummy position is added to reduce the number of constraints. Thereafter, $No+1$ positions are considered for each batch of each vehicle. The decision variables are as follows:

co_i	Completion time of order i in the suppliers stage
$Delivery_i$	Delivery time of order i to the factory
$Load_i$	Loading time of order i on the vehicles in order for transportation
Av_{mbi}	The time when vehicle i^{th} is ready to carry order i in its b^{th} mission
$Arrive_{mb}$	Arrival time of i^{th} batch of m^{th} vehicle
x_{si}	Equals 1, if i^{th} order is delivered to s^{th} supplier; otherwise, equals 0
y_{iq}	In the suppliers stage, if order i is placed before order q , it equals 1; otherwise, it equals 0
V_{mbip}	Equals 1, if the priority of p^{th} transportation at b^{th} transportation by vehicle m is related to the i^{th} order; otherwise, it equals 0
rSF_{mbs} (rFS_{mbs})	If vehicle m at its b^{th} batch travels from the factory to supplier s (from supplier s to factory), it equals 1; otherwise, it equals 0
$rSS_{mbs's}$	If vehicle m at its b^{th} batch travels from supplier s to supplier s' , it equals 1; otherwise, it equals 0

The mathematical model is as follows:

$$\text{Min } Z_1 = \sum_{i=1}^{No} \text{Delivery}_i \tag{1-1}$$

$$\begin{aligned} \text{Min } Z_2 = & \sum_{m=1}^{Nv} \sum_{b=1}^{No} \sum_{s=1}^{Ns} (rSF_{mbs} \times ESF_{ms} + rFS_{mbs} \times EFS_{ms}) \\ & + \sum_{m=1}^{Nv} \sum_{b=1}^{No} \sum_{s=1}^{Ns} \sum_{s'=1}^{Ns} (rSS_{mbss'} \times ESS_{mss'}) \end{aligned} \tag{1-2}$$

S.t.:

$$\sum_{s=1}^{Ns} x_{si} = 1 \quad i = 1, 2, \dots, No \tag{2}$$

$$x_{is} = 0 \quad \begin{aligned} & i = 1, 2, \dots, No \\ & s = 1, \dots, Ns \mid a(i, s) = 0 \end{aligned} \tag{3}$$

$$\sum_{m=1}^{Nv} \sum_{b=1}^{No} \sum_{p=1}^{No} V_{mbip} = 1 \quad i = 1, 2, \dots, No \tag{4}$$

$$\sum_{i=1}^{No} V_{mbip} \leq 1 \quad \begin{aligned} & m = 1, 2, \dots, Nv \\ & b = 1, 2, \dots, No \\ & p = 1, 2, \dots, No + 1 \end{aligned} \tag{5}$$

$$\sum_{i=1}^{No} \sum_{p=1}^{No} size_i \times V_{mbip} \leq Cap_m \quad \begin{aligned} & m = 1, 2, \dots, Nv \\ & b = 1, 2, \dots, No \end{aligned} \tag{6}$$

$$co_i \geq \frac{pt_i}{SS_s} - M(1 - x_{is}) \quad \begin{aligned} & i = 1, 2, \dots, No \\ & s = 1, 2, \dots, Ns \end{aligned} \tag{7}$$

$$co_i + M * (2 + y_{iq} - x_{si} - x_{sq}) \geq co_q + \frac{pt_i}{SS_s} \quad \begin{aligned} & i, q = 1, 2, \dots, No \\ & i < q \end{aligned} \tag{8}$$

$$co_q + M * (3 - y_{iq} - x_{si} - x_{sq}) \geq co_i + \frac{pt_q}{SS_s} \quad s = 1, 2, \dots, Ns$$

$$y_{iq} = 0 \quad \begin{aligned} & i, q = 1, 2, \dots, No \\ & i \geq q \end{aligned} \tag{9}$$

$$\sum_{i=1}^{No} V_{mbi(p+1)} \leq \sum_{i=1}^{No} V_{mbip} \quad \begin{aligned} & m = 1, 2, \dots, Nv \\ & b = 1, 2, \dots, No \\ & p = 1, 2, \dots, No \end{aligned} \tag{10}$$

$$\sum_{i=1}^{No} V_{m(b+1)i1} \leq \sum_{i=1}^{No} V_{mbi1} \quad \begin{aligned} & m = 1, 2, \dots, Nv \\ & b = 1, 2, \dots, No - 1 \end{aligned} \tag{11}$$

$$Load_i \geq Av_{mbi} - M * (1 - \sum_{p=1}^{No} V_{mbip}) \quad \begin{aligned} & i = 1, 2, \dots, No \\ & m = 1, 2, \dots, Nv \\ & b = 1, 2, \dots, No \end{aligned} \tag{12}$$

A Genetic Algorithm with Multiple Populations to Reduce Fuel Consumption in Supply Chain

$$Load_i \geq co_i \quad i = 1, 2, \dots, No \quad (13)$$

$$av_{mli} \geq \frac{disTS_s}{VS_m} - M * (2 - V_{m1i1} - x_{is}) \quad \begin{matrix} i = 1, 2, \dots, No \\ m = 1, 2, \dots, Nv \\ s = 1, \dots, Ns \end{matrix} \quad (14)$$

$$av_{mbi} \geq Arrive_{m(b-1)} + \frac{disTS_s}{VS_m} - M * (2 - V_{mbi1} - x_{is}) \quad \begin{matrix} i = 1, 2, \dots, No \\ m = 1, 2, \dots, Nv \\ s = 1, \dots, Ns \\ b = 2, \dots, No \end{matrix} \quad (15)$$

$$av_{mbi} \geq Load_q + \frac{disSS_{s's}}{VS_m} - M * (4 - V_{mbqp} - V_{mbi(p+1)} - x_{qs'} - x_{is}) \quad \begin{matrix} i, q = 1, 2, \dots, No \\ m = 1, 2, \dots, Nv \\ s, s' = 1, \dots, Ns \\ b = 1, 2, \dots, No \\ p = 1, 2, \dots, No \end{matrix} \quad (16)$$

$$Arrive_{mb} \geq Load_i + \frac{disST_s}{VS_m} - M * (2 - \sum_{p=1}^{No} V_{mbip} - x_{is}) \quad \begin{matrix} i = 1, 2, \dots, No \\ m = 1, 2, \dots, Nv \\ s = 1, \dots, Ns \\ b = 2, \dots, No \end{matrix} \quad (17)$$

$$Delivery_i \geq Arrive_{mb} - M * (1 - \sum_{p=1}^{No} V_{mbip}) \quad \begin{matrix} m = 1, 2, \dots, Nv \\ b = 1, 2, \dots, No \\ i = 1, 2, \dots, No \end{matrix} \quad (18)$$

$$rFS_{mbs} \geq V_{mbi1} + x_{is} - 1 \quad \begin{matrix} m = 1, 2, \dots, Nv \\ b = 1, 2, \dots, No \\ i = 1, 2, \dots, No \\ s = 1, \dots, Ns \end{matrix} \quad (19-1)$$

$$rSF_{ms} \geq V_{mbip} - \sum_{q=1}^{No} V_{mbq(p+1)} + x_{is} - 1 \quad \begin{matrix} m = 1, 2, \dots, Nv \\ b = 1, 2, \dots, No \\ p = 1, 2, \dots, No \\ i = 1, 2, \dots, No \\ s = 1, \dots, Ns \end{matrix} \quad (19-2)$$

$$rSS_{mbs's} \geq V_{mbqp} + V_{mbi(p+1)} + x_{qs'} + x_{is} - 3 \quad \begin{matrix} i, q = 1, 2, \dots, No \\ m = 1, 2, \dots, Nv \\ s, s' = 1, \dots, Ns \\ b = 1, 2, \dots, No \\ p = 1, 2, \dots, No \end{matrix} \quad (19-3)$$

Equation (1-1) represents the objective function of minimizing the total tardiness of orders.

Equation (1-2) represents the objective function of minimizing the total fuel

consumed by vehicles. Constraint set 2 indicates that each order should be allocated only to one supplier. Constraint set 3 prevents the allocation of orders to unauthorized suppliers. Constraint set 4 indicates that each order is only allocated to one vehicle and to only one of its batches. Constraint set 5 indicates that an order cannot be allocated to more than one position in batches and vehicles. Constraint 6 guarantees that in each cargo, the space occupied by the allocated orders does not exceed the vehicle's capacity. Constraint set 7 considers the completion time of each order in the suppliers. Constraint set 8 indicates that each supplier cannot process more than one order at a time. The constraints could be activated when two orders i and q are assigned to the same supplier s ($x_{is}=x_{qs}=1$). In this case, only one of the constraints may be activated at the same time. If order i has higher priority than q for being processed by supplier s ($y_{iq}=1$), then the second constraint will be activated. Otherwise ($y_{iq}=0$), the first constraint will be activated. Constraint 9 eliminates some dummy variables. Constraint 10 guarantees that if an order is not allocated to p^{th} priority of b^{th} batch of m^{th} vehicle, allocating the order to $(p+1)^{\text{th}}$ priority is not allowed. Constraint 11 guarantees that if an order is not allocated to b^{th} batch of m^{th} vehicle, allocating the order to $(b+1)^{\text{th}}$ batch is not allowed. Constraint sets 12 and 13 indicate that loading time for each order equals the maximum of the two values the complete time of the order, and the availability time of the vehicle.

Constraint set 14 determines the availability time of the vehicle used for carrying the order allocated to the first priority of its first batch. Constraint set 15 determines the availability time of the vehicle used carrying the order allocated to the first priority of a batch, according to the arrival time of the pervious batch. Constraint set 16 determines the availability time of the vehicle used for carrying the order allocated to a batch, according to the loading time of the order priority of the previous transportation and the transportation time between the corresponding

suppliers. Constraint set 17 determines the arrival time of a batch according to the loading time of the orders allocated to it. Constraint set 18 determines the delivery time of an order, according to the arriving time of a batch to the manufacturing company. Constraint set 19 determines the traveled routes by each vehicle for each of its batches. Constraint set (19-1) indicates that if an order is assigned to the first position of the b^{th} batch of vehicle m , then the route from factory to the related supplier should be taken by the b^{th} mission of this vehicle.

Constraint set (19-2) indicates that if an order is assigned to position p of the b^{th} batch of vehicle m and there is no assignment for the next position (it is the last order for transportation), then the route from the related supplier to the factory should be taken in the b^{th} mission of this vehicle.

Constraint set (19-3) indicates that if two orders of i and q are assigned to the same batch of a vehicle and order i should be conveyed exactly after order q , then the route between the related suppliers should be taken. A special case of the this problem in which transportation times between suppliers are considered negligible, and only the objective function of total order delivery time is considered, constitutes the problem studied by [Zegordi and Beheshti Nia, 2009a]. Since their problem is NP-Hard, the problem examined in this study is also NP-Hard and heuristic or meta-heuristic methods should be employed to solve them. In the following section a genetic algorithm is presented to solve the problem.

4. Problem Solving

The literature review shows that the generic algorithm has been used more than the other meta-heuristic methods. Hence, in this paper, the genetic algorithms is also used to solve the problem. In this section, a developed version of genetic algorithm, named Social Genetic

A Genetic Algorithm with Multiple Populations to Reduce Fuel Consumption in Supply Chain

Algorithm (SGA) with multiple populations, is used in order to solve the problem.

SGA consists of three populations in which the fitness function of each population is different from other populations. Due to the fact that the objective function is composed of two parts, each of the first two populations has a distinct fitness function and aims to minimize one of the two parts of the objective function. The third population tries to reduce the weighed total of the two parts. In other words, in the first population, those chromosomes are considered superior whose total order delivery times are lower. Likewise, in the second population, those chromosomes are considered superior whose total fuel consumptions are lower. However, in the third population, those chromosomes are considered superior whose weighted sums in the two objective functions are lower. Each of the first two populations is connected to the third population and they import their best chromosomes into the third population in each iteration. The overall structure of the SGA is presented in Figure 1. The number of chromosomes of each of these three societies is determined according to the *popsiz*e parameter, described below. Using multiple populations with distinct fitness functions in the proposed algorithm increases solutions diversity in the third population and decreases the risk of falling into the trap of local optimal solutions. Other features of SGA are as follows:

Chromosome structure: The structure of chromosomes in the proposed genetic algorithm is two-dimensional. The vertical dimension represents suppliers and vehicles. And the horizontal dimension represents the allocated orders and their priorities to each of suppliers and vehicles. For each of suppliers and vehicles, there is a string whose length and order respectively indicate the number and the order of the orders allocated to a supplier or a vehicle. If the number of orders allocated to suppliers or vehicles is changed, the length of the associated string will

also change. Figure 2 presents a feasible chromosome with 5 orders in a supply chain with 2 suppliers and 2 vehicles. In this chromosome, Order 1 is assigned to Supplier 1 and other orders are assigned to Supplier 2. Supplier 2 first processes Order 2 and then Orders 3, 5 and 4, respectively. Orders 5 and 3 are assigned to Vehicle 1 and others are assigned to Vehicle 2. Order 5 has higher priority for transporting by Vehicle 1 than Order 3. Similarly, Order 2 has higher transportation priority in Vehicle 2.

The steps required for generating a random chromosome in the algorithm for a problem with N_o orders, N_s suppliers and N_v vehicles are as follows:

Step 1- For each supplier s (vehicle v) let $POSITION_s=0$ ($POSITION_v=0$).

Step 2- Create a random permutation from orders.

Step 3- For $i=1$ to N_o

Randomly select a supplier namely s .

Let $POSITION_s = POSITION_s + 1$

Allocate i^{th} order in the created string in Step 2 to position $POSITION_s$ of supplier s .

Randomly select a vehicle namely v .

Let $POSITION_v = POSITION_v + 1$

Allocate i^{th} order in the created string in Step 2 to position $POSITION_v$ of vehicle v .

Step 4- Calculate the two objective functions for the chromosome considering the other parameters of the algorithm.

Fitness functions: The fitness function of each chromosome in the first society is defined as follows:

$$Fitness\ function = \frac{Z_1}{Z_1^{MAX}}$$

In which Z_1 is the total order delivery time for the corresponding solution and Z_1^{MAX} is the maximum Z_1 among the current generation of chromosomes.

Also, the fitness function of each chromosome in the second society is defined as follows:

$$Fitness\ function = \frac{Z_2}{Z_2^{MAX}}$$

In which Z_2 is the total fuel consumption for the corresponding solution and Z_2^{MAX} is the maximum Z_2 among the current generations of chromosomes.

Also, the fitness function of each chromosome in the third society is defined as follows:

$$Fitness\ function = w_1 \frac{Z_1}{Z_1^{MAX}} + w_2 \frac{Z_2}{Z_2^{MAX}}, w_1 + w_2 = 1$$

In which w_1 is the weight of the first objective function and w_2 is the weight of the second objective function. These weights can be determined according to experts' opinions or through Multi-Criteria Decision Making (MCDM) methods such as Analytical Hierarchy Process (AHP).

Crossover operator: in the proposed algorithm, Parameterized Uniform Operator has been used. Using roulette wheel, two parents are selected for the crossover operator. The parent with better fitness value is shown with p_1 and the other is named p_2 . Then, two random real numbers

between 0 and 1 is generated. In the generation of the child, if the first (second) random number is less than r (one of the parameters of the algorithm) then the chromosome genes of the child in the suppliers (transportation) stage is inherited from p_1 , otherwise, it is inherited from p_2 . The crossover rate is shown by *precross*. Figure 3 shows an outline of performing the Parameterized Uniform Crossover Operator with $r=0.7$.

Mutation operator: to perform mutation operator in SGA, a chromosome is selected randomly; then the reverse and swap operators are performed in two phases. In the first phase, two random positions in string of a random supplier (vehicle) are selected. Then, the gene sequence between these two points is reversed (reverse mutation). In the second phase, two random genes from the strings of two different suppliers (vehicles) are selected and are replaced with each other (swap mutation). The mutation rate is shown by *pemut*.

Each of the three societies performs mutation operation independently. Mutation operation in this algorithm is the same as the one in Dynamic Genetic Algorithm and uses a combination of reverse and swap operators. After each mutation operation, its fitness function is calculated based on the population type. The number of repetitions of the mutation operator in each iteration is constant and is determined by a factor of population size of each society, which is a parameter of genetic algorithm and is designated by '*permut*'.

A Genetic Algorithm with Multiple Populations to Reduce Fuel Consumption in Supply Chain

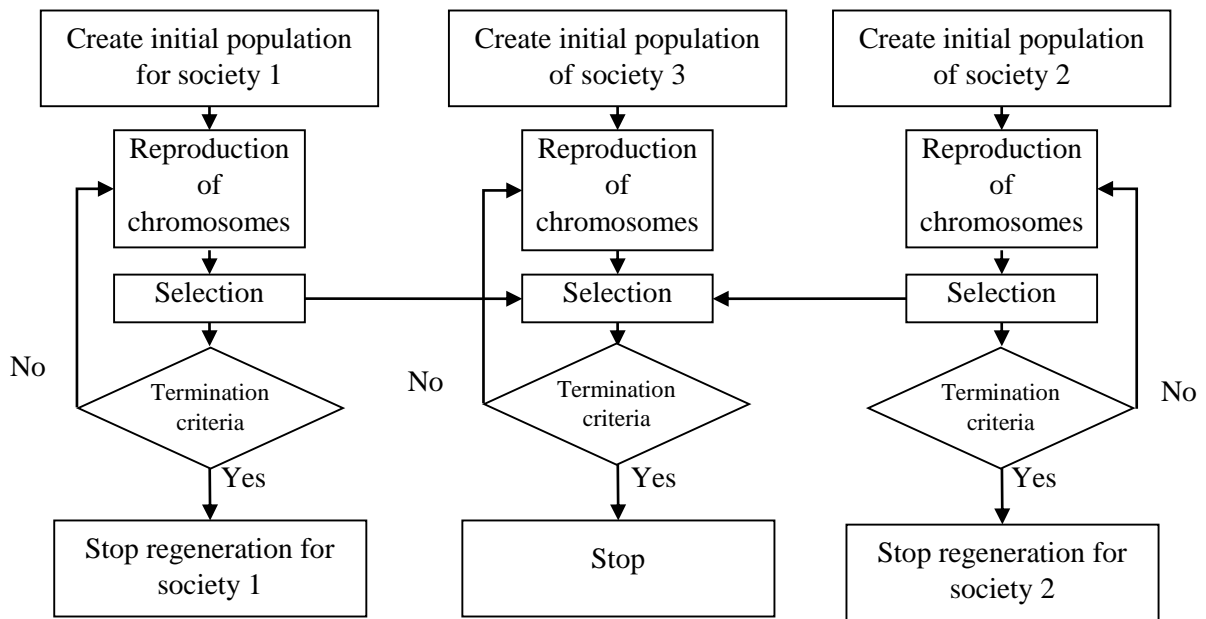


Figure 1. Structure of SGA

Supplier 1	1			
Supplier 2	2	3	5	4
Vehicle 1	5	3		
Vehicle 2	2	1	4	

Figure 2. A feasible chromosome

Supplier 1	1			
Supplier 2	2	3	5	4
Vehicle 1	5	3	1	4
Vehicle 2	2			

Chromosome p_1

Supplier 1	1	3	5	
Supplier 2	2	4		
Vehicle 1	5	3		
Vehicle 2	2	1	4	

Chromosome p_2

0.8	0.3
First random number	Second random number

Supplier 1	1	3	5	
Supplier 2	2	4		
Vehicle 1	5	3	1	4
Vehicle 2	2			

Child chromosome

Figure 3. Crossover operator in SGA

Selecting the next generation: in each of the first and second populations, a fraction of chromosomes in a generation which have a better fitness function are directly transformed to the next generation. Other chromosomes are selected based on roulette wheel operator. This fraction is a parameter of the genetic algorithm and is shown by *best*. As for the third society, $best/3 * popsize$ superior chromosomes of a generation are directly transformed to the new generation. In addition, $best/3 * popsize$ superior chromosomes of the first society and $best/3 * popsize$ superior chromosomes of the second society are transformed to the new generation of the third society. Other chromosomes of the third society are transformed to the new generation based on implementation of the roulette wheel operator on its previous generation.

Stopping criterion: In the proposed algorithm, if the best chromosomes in each population are not improved in a few consecutive iterations, repetitions would stop in that population. The number of these consecutive iterations is one of the parameters of the algorithm, which is shown by *ter_num*. If the iterations in the third population are stopped, the whole algorithm would stop and the best chromosome in this population is introduced as the final solution.

Empirically and after several runs, the values 100 for the parameter '*popsize*', 0.6 for the parameter '*percross*', 0.8 for the parameter '*permut*', 10 for the parameter '*ter_num*', 70 for the parameter '*best*', and 0.7 for the parameter *r* are chosen.

5. The Numerical Experiments

To evaluate the performance of SGA, it is compared with a single population genetic algorithm that is a developed version of the Dynamic Genetic Algorithm (DGA), proposed by [Zegordi and Beheshti Nia, 2009a]. Then, the results obtained from using this algorithm for small-size problems are compared with the optimal solution. Finally, the sensitivity analysis

is performed on some of the main parameters of the problem.

5.1 Comparison with Single Population Genetic Algorithm

As mentioned earlier, in order to evaluate the performance of SGA, it is compared with the single population version of the algorithm which is in fact a developed version of DGA, proposed by [Zegordi and Beheshti Nia, 2009a]. To have a fair comparison, DGA has the same operators and parameters as SGA; but it has a different population size ($3 * popsize$). The fitness function in this algorithm is considered combinational and similar to the fitness function of the third population of SGA.

5.1.1 Generating Test Data

The validity of a comparison will increase, if the results obtained from the two algorithms are compared using a diverse range of test problems. For example, one algorithm may produce better results for problems with low number of orders and worse results for problems with high number of orders. The problem has different variables. For a better performance evaluation, it is better to create diverse problems with different values for its parameters. For this purpose, three levels of high, average, and low are considered randomly. The parameters are divided into seven categories as shown in Table 1.

For the number of orders three values of 10, 50, and 100 have been considered. For the supplier and vehicle parameters three cases have been considered. The first and the third cases are unbalanced, and the second case is balanced. In the first case, the number of suppliers is selected from the uniform distribution $U[1,5]$, and the number of vehicles is selected from the uniform distribution $U[10,15]$. The third case is the reverse of the first case. The same approach

A Genetic Algorithm with Multiple Populations to Reduce Fuel Consumption in Supply Chain

is followed for the processing time and distance parameters with different distributions. Also, for the vehicle capacity, two cases are considered. Other values are considered as shown in Table 1. Therefore, 54 different problems have been created using different combinations of the different levels ($3*3*3*2*1*1*1$) and the two algorithms of DGA and SGA have been implemented on them.

5.1.2 Computational Results

The comparison results for both algorithms are shown in Tables 2, 3 and 4. In Table 2, it is assumed that $W_2=W_1=0.5$, meaning that is the objective functions have equal weights. In Table 3, it is assumed that $W_1=0.2$ and $W_2=0.8$, which indicates that the weight of the second objective function is more important than that of the one of the first objective function. In Table 4, results are compared assuming that $W_1=0.8$ and $W_2=0.2$, indicating more importance for the weight of the first objective function than the weight of the second objective function.

Results indicate the better performance of the SGA than the DGA. The results also indicate that

by increasing in the number of orders, the average of solutions and the average solving time are also increased. In the case of the numbers of suppliers and vehicles, the results are different for different weights of objective function. When the weights of the objective functions are the same (see Table 2), the best result is obtained when there is a balance between suppliers and vehicles (Case 2). Among unbalanced cases, Case 1 is better than Case 3, which means that the number of suppliers has a greater impact on the problem than the number of vehicles. However, when the weight of the objective function of total fuel consumption is more than that of total order delivery time (see Table 3), results demonstrate that the number of vehicles has more effect on the objective function and by increases it, the value of the objective function is decreased. When the weight of the objective function of total order delivery time is more than that of total fuel consumption (see Table 4) reverse results will be obtained and the best results are achieved when there is a greater number of suppliers.

Table 1. Generate random data

	Level 1	Level 2	Level 3
Number of orders	10	50	100
Number of vehicles	U[1,5]	U[5,10]	U[10,15]
Number of suppliers	U[10,15]	U[5,10]	U[1,5]
Processing time	U[1,10]	U[10,20]	U[20,30]
Distances	U[20,30]	U[10,20]	U[1,10]
capacity	U[10,20]	U[20,30]	-
Order volume	U[1,5]	-	-
Vehicle speed	U[1,3]	-	-
Supplier speed	U[1,3]	-	-

Table 2. Comparison of the results of SGA and DGA (W1=0.5,W2=0.5)

Parameter	Level	Average of solutions		Average CPU time (seconds)	
		SGA	DGA	SGA	DGA
Number of orders	Low	463.1	467.8	79.8	60.8
	Average	2969.4	3155.9	2254.1	2182.6
	High	6270.1	6823.3	4313.7	4689.8
Number of suppliers and vehicles	Case 1	3292.5	3580.2	3605.1	3735.7
	case 2	2997.3	3109.1	1967.5	2145.7
	Case 3	3412.7	3757.8	1089.7	1070.1
Processing time and distances	Case 1	2071.9	2189.9	2059.8	2099.4
	Case 2	3331.6	3550.5	2198.6	2389.3
	Case 3	4299.1	4706.7	2392.2	2462.3
Vehicle capacity	Level 1	3390.4	3619.4	1974.1	2009
	Level 2	3078	3345.4	2458.4	2625.3
Total Problems		3234.2	3482.4	2215.9	2317.7

Table 3. Comparison of the results of SGA and DGA (W1=0.2,W2=0.8)

Parameter	level	Average of solutions		Average CPU time (seconds)	
		SGA	DGA	SGA	DGA
Number of orders	low	537.8	544.1	77.8	56.1
	average	2821.1	3055.3	2091.1	1992.6
	high	4641.8	4948.7	4355.2	4561.8
Number of suppliers and vehicles	Case1	3120.9	3541.9	3599.1	3621.5
	Case2	2485.1	2510	1941.1	2115.7
	Case3	2395.2	2495.5	986.8	975.1
Processing time and distances	Case1	2055.4	2190.1	2011.9	2050.6
	Case2	2787.1	2889.4	2264.5	2300.4
	Case3	3158.9	3467.4	2241.3	2262.3
Vehicle capacity	Level 1	2735.5	2860.3	2302.3	2411.3
	Level 2	2580.6	2838.4	2048.1	1989
Total Problems		2667.1	2849.4	2175.7	2203.8

Table 4. Comparison of the results of SGA and DGA (W1=0.8,W2=0.2)

Parameter	level	Average of solutions		Average CPU time (seconds)	
		SGA	DGA	SGA	DGA
Number of orders	low	388.5	391.7	74.8	68.9
	average	3032.5	3255.5	2341.1	2032.6
	high	7915.3	8681.3	4132.2	4689.8
Number of suppliers and vehicles	Case1	3396.4	3602.4	3654.1	3895.5
	Case2	3506.9	3707.6	1931.1	2039.7
	Case3	4432.9	5015.5	966.8	850.1
Processing time and distances	Case1	2026.3	2184.4	1999.9	2049.6
	Case2	3870.9	4212.2	2190.5	2279.4
	Case3	5439.1	5928.9	2362.3	2462.3
Vehicle capacity	Level 1	4004.5	4375	2292.2	2541.3
	Level 2	3553.1	3842	2047.1	1986
Total Problems		3778.8	4108.9	2183.7	2263.8

As for process times and distances, results show that the best results are obtained when the processing time is lower. This means that the effect of this parameter is more than the distance parameter. Furthermore, results show that with an increase in vehicle capacity, the average of solutions as well as the solving time are decreased.

5.2 Comparison with Optimum Solution

In the following, SGA is compared with the optimal solutions of several small-size problems. Table 5 shows the results of the comparison of SGA with the optimal solutions of several random small-size problems. The optimal solution is determined by running the model in the GAMS software. In this table, each problem is indicated by three numbers. The first one shows the number of orders; the second one is the number of suppliers; and the third one is the numbers of vehicles. Other parameters of the problem are generated according to the previously mentioned distributions (see Table 1). Results show that in most cases, the SGA gives the same solution as the optimal solution; and in the other cases the difference is low. Also, the

solving time for the proposed algorithm is much less than optimal solving time.

5.3 Sensitivity Analysis

In this section, a sensitivity analysis for the main parameters of the problem is performed. These parameters include the number of orders (No), the numbers of suppliers (Ns), and the number of vehicles (Nv). 5 levels are considered for each of these three parameters and the effect of changing each parameter on the objective function is examined when the other parameter are constant. Other parameters are determined as follows: The process times and the distances are selected from the uniform distribution $U[10,20]$; the vehicle capacities are selected from $U[10,20]$; the speeds of suppliers and vehicles are selected from $U[1,3]$; and the orders size are selected from $U[1,5]$, $w_1=0.5$ and $w_2=0.5$.

For each case 20 test problem are generated randomly and solved by SGA. Table 6 and Figure 4 show the effect of changing the parameters of No , Ns , and Nv on the average of the obtained objective functions.

Results show that with an increase in N_o , the objective function is increased; also, with an

increase in N_s and N_v , the objective function is decreased.

Table 5. comparing the results of the proposed algorithm with the optimal answer

Problem No.	Problem specifications	SGA		Optimal solution	
		Solution	CPU time (seconds)	Solution	CPU time (seconds)
1	6×2×2	242.531	26	242.531	53
2	6×3×2	238.755	30	238.755	36
3	6×2×3	240.838	20	240.838	35
4	7×2×2	265.734	15	243.724	2368
5	7×2×1	268.127	29	249.276	947
6	7×1×2	252.528	32	252.528	3537
7	7×3×2	258.506	13	247.074	1080
8	7×2×3	247.521	49	247.521	813
9	7×3×3	259.721	36	246.186	632
10	7×4×4	243.376	22	243.376	616

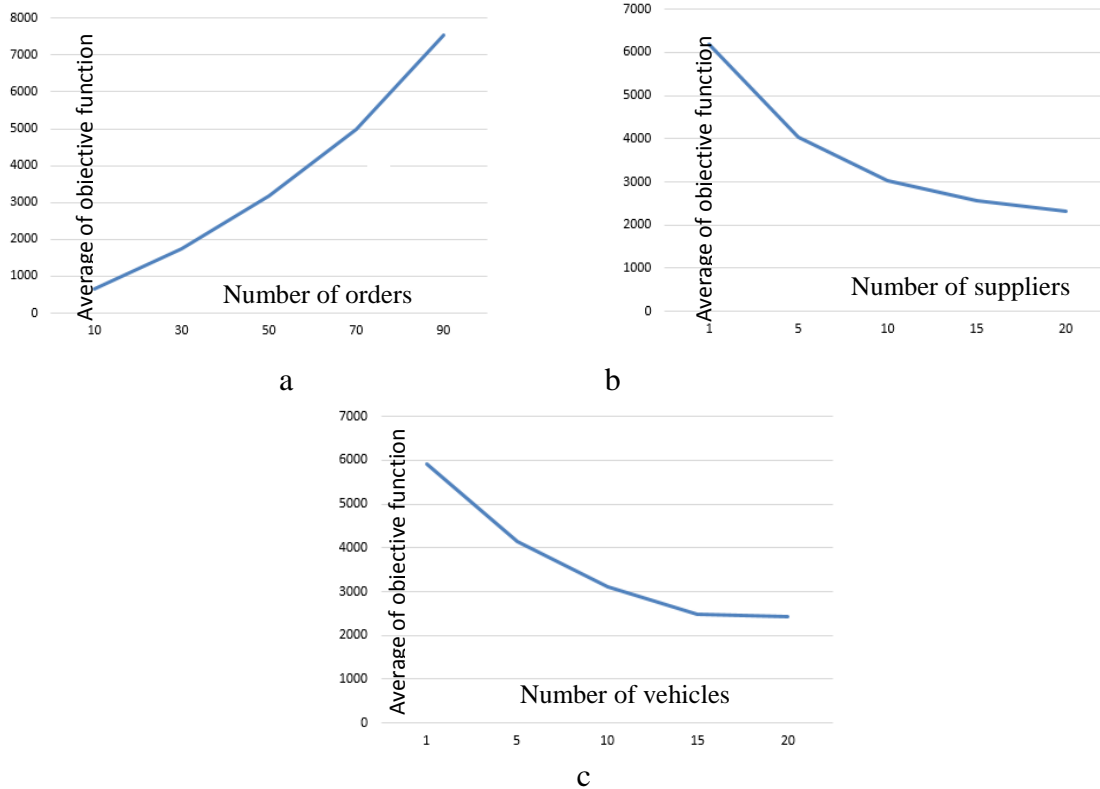


Figure 4. Changes in objective function with changes in the number of orders, suppliers and vehicles

Table 6. the changes in objective function according to the changes in problem parameters

Problem Number	$N_s=10, N_v=10$		Problem Number	$N_o=50, N_v=10$		Problem Number	$N_o=50, N_s=10$	
	N_o	Average of solutions		N_s	Average of solutions		N_v	Average of solutions
1	10	653.735	1	1	6188.503	1	1	5921.681
2	30	1746.97	2	5	4022.527	2	5	4145.177
3	50	3172.862	3	10	3016.895	3	10	3108.882
4	70	4973.059	4	15	2564.361	4	15	2487.106
5	90	7553.584	5	20	2307.925	5	20	2437.364

6. Research Summary and Future Research Scopes

Many manufacturers try to reduce their finished product cost. A major part of the final cost of a product is related to transportation costs in the supply chain. Reducing the transportation fuel consumption directly reduces transportation costs. Also, it reduces environmental pollution, and in some cases, it helps governments constitute less subsidies for fuels. This paper tries to minimize the fuel consumption of the transportation fleet in a supply chain. Another objective function of the problem is minimizing total orders delivery time. The supply chain studied in this paper consists of three stages. The first stage includes the suppliers; the second stage involves the transportation fleet; and the third stage includes the manufacturing company of final products.

First, the mathematical model of the problem was presented and then a genetic algorithm with multiple populations, named SGA, which has chromosomes with variable structures were introduced to solve it. In order to evaluate the performance of SGA, its results compared with a single population genetic algorithm and the optimal solution for randomly generated test problem. Finally, a sensitivity analysis for the main parameters of the problem is performed.

The result of the comparison between SGA and the optimal solution show the high performance

of SGA. The comparison between SGA results and the single population version of it also shows the better performance of SGA. The reason is that in the single population genetic algorithm a good chromosome in a population will lead to the solutions converge into a local optimum solution. In SGA however, this causes the solutions to converge into a population and other populations continue generating new chromosomes. Also, the third population always receives chromosomes from other two populations which have different fitness functions, resulting an increase in diversity of solutions.

Moreover, results show that by increasing the number of suppliers and vehicles the value of the objective function is reduced. The reason is that the average workload of each supplier and vehicle is reduced, which leads to a decrease in the total order delivery time. Moreover, by decreasing the total workload of each vehicle, the number of its round-trips are eliminated and the fuel consumption is reduced. Similarly, the objective function value is decreased by reducing the number of orders.

Determining the allocation of orders to the suppliers and vehicles, together with production and transportation scheduling is a complex decision making process; because, each decision about one of them affects other decisions. The proposed algorithm helps supply chain managers make proper decisions in order to minimize total order delivery time and fuel consumption. Moreover, reducing fuel consumption causes a decrease in environmental

pollution and in some cases, it helps governments constitute less subsidies for fuels.

The integration level of considered supply chain consists of a manufacturer and its suppliers. Expanding this integration level to cover the distributors or multiple parallel manufacturers may be considered for future research. Adding other objective functions such as minimization of total tardiness time could also be studied in future researches. From the aspect of the used algorithm, using the proposed populations structure for other supply chain scheduling problems could be another subject for future research.

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