Mathematical modelling of the vehicle hybrid locating-routing problem in three-tier supply chain

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Abstract: One of the important issues that has been widely used and raised to improve efficiency of transportation systems is vehicle routing problem (VRP) in recent decades. This study has examined complex integer mathematical model in three-tier supply chain. In this paper, three-objective mathematical model was presented for location and routing problem. The presented model was raised in three-tier supply chain in which products are shipped from manufacturers to distribution and from distribution to customers. In this study, we aim to design three-tier supply chain network that wants to reduce costs, which results in increased profits, and also to maximise quality of products. The above problem was introduced and multi objective mathematical model is provided. The exact method is used to solve MILP model. The results show that the total cost of system, including transport costs, maintenance reduced and as well as balanced distribution of costs and quality will increase.

Keywords: location-routing; supply chain; hybrid algorithm; simulation; VRP; vehicle routing problem.

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1 Introduction

Transportation is one of the main and important sectors of economy of each country and is one of the most important components of final cost of finished product. One of the attractions of transportation is its economic value in development country or its effectiveness in profitability of companies and organisations. The main goal of the transportation problem is to minimise cost of transporting goods and materials between two levels of production and consumption, so that the demand for each consumer should be satisfied by manufacturer.

One of the important activities which are done in logistics distribution network is supply chain routing. Efficient routing for supply chain is important both for private and public sectors economically (Patricia et al., 2009). The transfer of raw materials and primary components from their supply sources to production lines, their transfer between factories before final production, and ultimately the transfer of final products to customers is very necessary (Baldacci et al., 2009).

After the economic crisis in the 1970s and 1980s, research centres and companies sought to find new ways to reduce costs in various parts of supply chain (Baldacci et al., 2009). Therefore, to improve costs, routing in supply chain was carried out in a variety of ways. High dependence on supply and distribution network and sale of goods and services has led companies, institutions and service providers think about new approaches in line with achieving their goals with due consideration of efficiency and effectiveness that can help them in this regard.

New approaches adopted were used aimed to integrate as many supply chain elements as possible and seek to integrate decisions of various activities such as distribution process, inventory control decision making, and supply chain production and routing in an optimisation model. In the meantime, the issue of routing has been more in the interest of scientific community, although this is less inferred from the point of view of supply chain management (Bard, 2009).

In recent years, many improvements have been due to correct exchange of information between different levels of a supply chain. The supply chain is often referred to as a supply chain network, which includes nodes that represent facilities. The flow can only be transmitted between two successive stages of levels of a supply chain network. The three-tier supply chain issue involves selection of facilities (distribution centres) that need to be established and designed of a distribution network that needs to meet demand at minimum cost. The strategy of manufacturers and distribution centres has a significant effect on the design decisions of supply chain network. Therefore, the present study, based on presentation of a mathematical model, chooses the optimal route with the least cost, taking into account the time factor by time windows in the three-tier supply chain network.

Also, in this study, the capacity of non-homogeneous vehicles is considered and Because of the importance of quality of raw materials for manufacturers and consumers, in the third objective of mathematical model, we want to maximise quality of products with respect to raw materials. Further, in other sections, we will discuss with the following: First, the problem will be discussed, and then the proposed model will be presented in the next section, and then the proposed method of solving in order to solve the model, and finally, the results will be examined.

2 Literature review

The vehicle routing problem (VRP) was formulated for the first time by Ramser (1950) and solved by mathematical methods. According to a set of constraints, VRP is used to design a favourable route for a fleet of vehicles to serve a set of customer orders. In order to optimise the physical flow of goods and services, VRP is used in supply chain management (SCM).Dantzig and Fulderson (1954) presented a zero-one mathematical model to solve VRP. Clark and Wright (1964) proposed a saving algorithm for solving VRP, which was the basis for many further researches, So that many methods were proposed based on Clark and Wright (1964) method and creating minor changes in it. Among the works that have been conducted in the past years in the field of VRP studies, we can mention works carried out by Tat et al. (2007). The classic VRP alone is not realistic, since most companies have access to a fleet of transportation. In this case, unlike classic VRP, the objective function is to minimise the total fixed costs of vehicles and variable costs of the routing, and the routing costs depend on the total distance travelled.

Patricia et al. (2009) reviewed a paper on locating-routing problem with time windows. In this problem, which was solved by branch and price method, the main problem was formulated as a cover of set. Also, pricing problem was formulated with regard to constraints of finding the shortest route, window time limits, and capacity constraints. The biggest problem was solved by this algorithm included 20 customers.

Brandao (2011) designed for the first time an Ant system to solve VRP. This algorithm was later improved by combining it with an innovative method of saving. Also, Ropke and Pisinger (2011) presented an algorithm for decomposition -based on ant-system (D-Ants) for CVRP problem. In this algorithm, the problem is decomposed into several sub-problems, and each sub-problem is solved using a savings-based ant-colony system.

In recent years, among the work done on the application of ant colony algorithm, We can note to the work of Mehravaran et al. (2012) for the problem of VRPBTW, Zhen and Zhang (2009) for the CVRP problem, Gajpal et al. (2009), for the problem of VRPB, in general mode with the limited number of identical vehicles, which introduced a combined algorithm, including clone colonies and closest neighbours for VRP.

Also, in a case study in Euchi et al.,(2012) has used a hybrid algorithm, including an ant colony and local neighbourhood search method to school bus routing problem in a city environment that is a special case of VRP.

Tavakkoli-Moghaddam and Safaei (2007) proposed a simulated annealing algorithm for VRPSS problem in the case that transports fleet is HFVRP type. Min et al. (1992) introduced an innovative column manufacturing algorithm for these problems. Since in the process of dividing demand, a client may want to meet all his demands a full request at a meeting. Gulczynski et al. (2010) suggested a particular mode of problem for when a minimum customer demand for a vehicle should be met and used a banned search algorithm to solve it. Also, Gulczynski et al. (2010) developed the demand division problem for a state of the VRP with multiple depots, and provided an integer programming approach based on the proposed method and showed that proposed method has produced for high-quality solutions for the test problems.

Some practical examples of this issue include Kang et al. (2007), which there is a neighbourhood search algorithm for the routing problem in maritime transport, when it is possible to process cargo loading by several ships, as well as Righini et al. (2008), for the routing problem in the state of harvesting and delivering in the shipping of crude oil. Yang et al. (2015) also studied problem of optimising time-based environmental routing and multiple types of devices, taking into account the concept of carbon reduction strategies, along with a genetic hybrid algorithm. Lee et al. (2010) have proposed a systematic locative method based on local search for VRP of a multi-warehouse with simultaneous harvesting and deliverables, which suggested new operations to diversify search, which computational results indicate that the proposed method has a better performance than previous methods. Zachariadis et al. (2015) examined VRP, which is called LDVRP (the total of route travelled and gross weight transported over this distance), the investigator proposed a local search algorithm which uses a computational algorithm that calculates objective changes of distance-weight of the set permanently and shows the solution results for both problems in types of known test samples that indicate effectiveness of problem-solving approach.

Considering that this model is considered as a three-tier model, in leasing companies, the demand for each period of time may be greater than capacity of each vehicle, So, delivery of goods to any customer may be done for more than a vehicle to meet all customer demands in each period. In literature, it is generally assumed that demand of each customer is less than the capacity of each vehicle, while in reality it is not.

Therefore, innovation of this research is that delivery of goods is done individually, so that more than one vehicle can deliver to each customer, who was introduced by Dror and Trudeau (1990) for the first time.

Goodarzi and Zegordi (2016) considered a location-routing problem in a distribution network consisting of several suppliers, cross dockings, and assembly factories (as customers). They modelled the problem as an MINLP to determine the location of warehouses, allocate suppliers to the warehouses, and make routing decisions in a way that locating and transportation costs would be minimised in the network. Since the location-routing problem is a hybrid of FLP and VRP, both of which are NP-HARD problems, it is an NP-HARD problem. Therefore, the biogeography-based optimisation (BBO) algorithm was used to solve the problem. Furthermore, some small problems were investigated to compare the efficiency of the algorithm. Also Puga and Tancrez (2016) presented a heuristic algorithm to solve the location inventory problem with huge dimensions in a two-tier supply chain (including retailers, distribution centres, and a central factory) in addition to investigating available models for the location-inventory problem with uncertain demands. In 8the proposed model, three classes of decisions are integrated at the same time. These decisions include the number and location of facilities which start working, the allocation of flow to facilities and retailers and finally the inventory decisions. The aim of solving the problem is to minimise the costs of inventory, transportation and location-allocation in a way that retailer demands are met, and a specific level of service is guaranteed. Ulmer et al. (2017) proposed a Markov decision process (MDP) for dynamic routing problems and showed that route-based MDPs are equivalent to the conventional MDP model. Sayarshad and Chow (2017) proposed a new queuing-based formulation of the online problem of relocating idle vehicles in demand-responsive systems.

In this study, contrary to previous studies, we are going to provide mixed integer linear programming (MILP) multi objective mathematical model which there are three objective functions that are to minimise total cost of supply chain; transport time in supply chain network and also, we try to maximise quality of raw materials shipped from suppliers, taking into account the time of transfer with considering the limits of capacity and travel time of vehicles and distribution centres.

2.1 Past studies on supply chain management and vehicle navigation:

Table 1 shows some of the most important research done in the field of supply chain management. It should be noted that respected researchers who are interested in research activities in the field of supply chain management and vehicle navigation, with the focus of these papers, can reach the relevant authorities for their research topics.

Table 1 Some of the most important research in the field of supply chain management and routing

Year	*The authors*	*Content of the paper/book*
2012	Khaled Abdallah and Jaejin Jang	A precise solution to automotive routing problems with limited hard-core resources
2013	Nekooghadirli and Tavakkoli-Moghaddam	Solve the problem of double-target new inventory routing in a distributed meta-explorer network
2013	Martin Dario Arango Serna	Vehicle routing to multiple warehouses using a meta-heuristic algorithm
2014	Jun Peia and Xinbao Liu	Solve the supply chain program problem with the same workload and free load using an effective time algorithm
2014	Chong Li and Sifeng Liu	Random network model and sensitivity algorithm for time analysis and order inventory in multi-stage supply chain
2014	Reza Nasiri and Rohollah Zolfaghari and Hamid Davoudpour	Supply chain integration Product-distribution planning with random demands
2014	Florian. Behncke and Florian and Walter	One way to match network design with supply chain and product architecture
2014	Yohanes Kristianto and Angappa Gunasekaran	Flexible model supply chain network design: two-stage programming with the shortest fuzzy path
2014	Cardona-Valdés and Álvarez and Pacheco	A metropolitan method for a supply chain with uncertainty

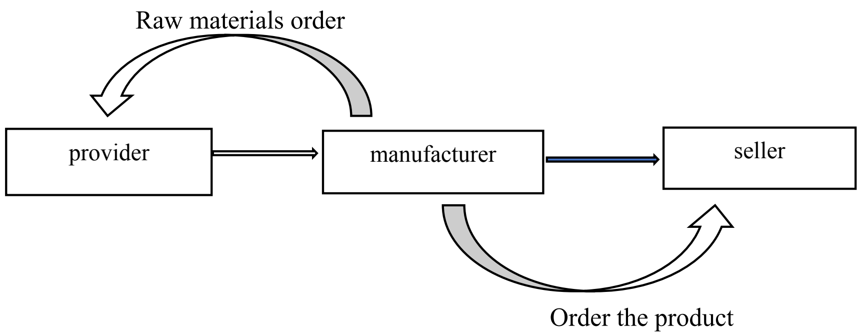
Table 1 Some of the most important research in the field of supply chain management and routing (continued)

Year	*The authors*	*Content of the paper/book*
2014	Dimitris Mourtzis and Michalis Doukas	A toolkit for designing, planning and operating a supply chain in a massive customisation environment
2014	Law and lee	The use of intelligent data management in resource allocation for the effective operation of production and supply chain systems
2014	Ashkan Negahban and Jeffrey Smith	Simulation for design system production and exploitation: literature review and analysis
2015	Mustafa Avci, Seyda Topaloglu	A local search adaptive algorithm for solving vehicle voyage and delivery simultaneously and mixed
2015	Gulcin Dinc Yalcın, Nihal Erginel	Fuzzy multi-objective programming algorithm for automobile routing problems with backhauls
2015	ibrahim Çapar and Burcu B. Keskin and Paul A. Rubin	Improved formula for covering the maximum routing problem
2015	Voratas Kachitvichyanukul	Two solutions for car routing and delivery simultaneously via pso

3 Problem statement and definitions

In this study, a three-tier supply chain network including manufacturing centres, distribution centres and customers is considered in which products are first sent from manufacturing centres to non-homogeneous transportation vehicles and sent to distribution centres and then to customers by machines. The general shape of network is presented in Figure 1. In spite of all criteria for a supply chain model in this study, the dynamism of model is well represented in its manufacturing planning and inventory. Therefore, this chain model is a new and complete model of previous models.

Figure 1 Supply chain network



Source: Soufifard et al. (2006)

Model assumptions:

- There is a three-tier distribution network.
- Factories produce different products.
- Products are sent from factories to customers.
- Given the fact that demand of some customers is more than vehicle capacity, more than one vehicle can be imported to each customer.
- Vehicles have different capacities.

Indices and models:

p: Number of manufacturing centres.

m: Number of distribution centres.

n: Number of customers.

k: Manufacturing centres k. $k = \{1,2, \ldots, K\}$

j: distribution centre j. $j = \{1,2, \ldots, J\}$

i: Index of node. $i = \{m + 1, m + 2, \ldots, m + n\}$

O: Index of raw material, $o = \{1, 2, ..., O\}$

T: Index of period: $t = \{1,2, \ldots, T\}$.

Q: Vehicle capacity in the network routing section.

W: Set of capacity levels available to distribution centre.

Model parameters:

a_k: Maximum production capacity of manufacturing centres k.

d_{kj}: Cost of sending a vehicle from manufacturing centre k to distribution centre j.

R: The capacity of vehicles that send products from distribution centres to production centres.

g_j: The fixed cost of building and distribution centre j.

b_j: The capacity of the j distribution centre.

h_i: Customer demand

c_{ij}: cost of transferring products from customer i to customer j in the network routing section

t_{ij}: Travel time from node i to node j.

W_{kj}: The capacity of manufacturing centre k to customer j.

Q_{otij}: The quality of raw material o which is sent from supplier i to producer j at tth period.

[Ej, Lj]: The time window for receiving product for the customer j.

Decision variables:

$y_i = \{0,1\}$: If distribution centre is constructed, 1 and otherwise, 0.

$Z_{ij} = \{0,1\}$: If the customer i is assigned to the distribution centre j, 1 and otherwise 0.

$x_{oi}^{(j)} = \{0,1\}$; If the node i is the first customer on the route of distribution centre j, and otherwise 0.

$x_{io}^{(j)} = \{0,1\}$: If the node i is the last customer on the route of distribution centre j, and otherwise 0, $X(j)$ io.

$x_{il}^{(j)} = \{0,1\}$: If the customer i after the customer l meets on the route of distribution centre j, and otherwise 0, X(j) io.

x_{ijzt} : The amount of raw material flow o from the supplier's centre i to the manufacturer's centre j in the period t.

3.1 Problem formulation

Base on the above definition of problem, the mathematical model is presented as follows:

$$\min z_1 = \sum_k \sum_j d_{kj} w_{kj} + \sum_j g_j y_i + \sum_j \sum_i (c_{ij} X_{0i}^{(j)} + c_{ij} X_{i0}^{(j)}) + \sum_j \sum_i \sum_{\substack{l \\ i \neq l}} c_{ij} X_{il}^{(j)}$$

$$\min z_2 = \sum_i \sum_l \sum_j t_{ij} X_{il}^{(j)} + \sum_j \sum_i (t_{ij} X_{0i}^{(j)} + t_{ij} X_{i0}^{(j)}) .$$

$$\max z_3 = \sum_i \sum_j \sum_o \sum_t (Q_{Otij} + X_{ijzt} + t_{ij}) .$$

S.t:

$$p\left\{ \sum_j V_{kj} \leq a_k \right\} . \tag{1}$$

$$w_{kj} \geq \frac{V_{kj}}{R} . \tag{2}$$

$$\sum_k V_{kj} < b_j y_j . \tag{3}$$

$$\sum_k V_{kj} \leq \sum_i h_i z_{ij} . \tag{4}$$

$$\sum_{j} z_{ij} - 1 . \quad (5)$$

$$\sum_{j} X_{0i}^{(j)} - \sum_{i} X_{i0}^{(j)} . \quad (6)$$

$$\sum_{\substack{i \\ l \neq i}} X_{il}^{(j)} = z_{ij} . \quad (7)$$

$$u_i - u_1 + Q \sum_{k} x_{il}^{(j)} \leq Q - h_l . \quad (8)$$

$$h_i \leq u_i \leq Q . \quad (9)$$

$$u_i \geq 0 . \quad (10)$$

$$y_j \in \{0\ .1\},\ z_{ij} \in \{0\ .1\};\ X_{0i}^{(j)} . X_{i0}^{(j)} . X_{il}^{(j)} \in \{0\ .1\} \quad (11)$$

$$V_{kj} \geq 0\ ; u_i w_{kj} \geq 0\ , \text{integer} . \quad (12)$$

$$Y_{mjt} \cdot E_j \leq TI_{mjt} \leq l_j \cdot Y_{mjt}\ ; \vartheta m \in M\ . j \in J\ . t \in T . \quad (13)$$

Objective function (1) is to minimise the total cost of supply chain. Objective function (2) is to minimise transport time in supply chain network. And also, Objective function (3) is to maximise quality of products with respect to raw materials; Constraint (1) shows the capacity limitations of manufacturing centres as probable. Constraint (2) indicates the number of devices required per manufacturing centre. Constraints (3) and (4) indicate the capacity constraints of distribution centres. Constraint (5) shows that each customer is assigned only to a distribution centre. Constraints (6) and (7) are related to the routing constraints and Constraints (8) and (9) are restrictions for the removal of the sub-tour. Constraints (10)–(13) also represent the type of decision variables and their possible values. Constraint (15) is related to the variables zero and one. Constraint (16) states the time window allowed to serve each customer.

4 Research methodology

The statistical population of this study is all leasing companies with accreditation and accreditation accepted by the central bank of Iran. According to the latest information, there are currently 37 leasing companies from the central bank. 25 companies have License and 12 companies are extending licences from the central bank. For coding and solving the model, GAMS 24.1.3 software is used. The time to solve the model is 5566.179 s or 3 min. The values of the first objective function, Z_1, the second objective function, Z_2, and third objective function, Z_3 are the average time obtained. Table 2 shows the results of the first, second, and third objective function, and the mean solution time.

Table 2 Results from model solving

The size of the problem	*Number of Reps*	*Average first objective function*	*Average second objective function*	*Average third objective function*	*Average solving time*
3-5-10	10	5304654.782	280.241	234525.81	*1.154*
		5212980.407	240.588	601308.17	*2.684*
		5068378.054	439.471	779832.68	*1.349*
		4832036.623	613.784	1185074.95	*3.097*
7-5-15	10	7082924.222	550.902	81102.22	*22.912*
		6771709.742	654.875	891200.76	*4.525*
		7226746.456	534.387	413134.96	*1.344*
		6258657.392	818.977	96033.14	*2.706*
10-15-30	10	25996863.38	2537.657	985195.35	*220.371*
		23496477.24	3067.014	1706550.41	*368.241*
		25988350.15	4665.653	206621.90	*46.725*
		23286152.29	4896.603	1111490.28	*414.762*
15-20-50	10	76791041.93	1332.512	133329.27	*6391.469*
		63478996.02	3512.589	127295.44	*1592.947*
		77140076.7	5083.217	245538.20	*5097.997*
		68153167.91	6131.887	1186788.84	*1008.227*

The results of model solving in this software show that with increasing size of problem, the exact resolution time will be greatly increased (Figures 2–4).

Figure 2 The average of the first objective function in problems with different sizes (see online version for colours)

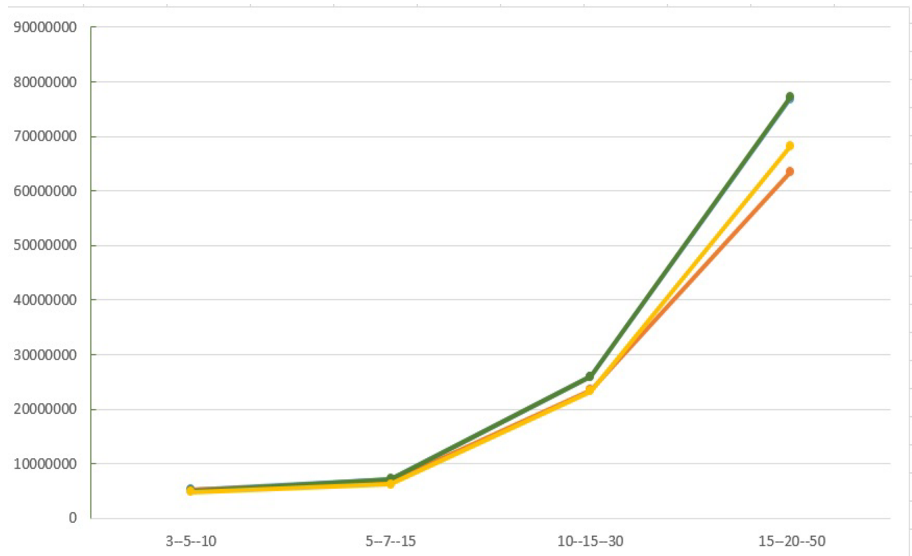


Figure 3 The average of the second objective function in problems with different sizes (see online version for colours)

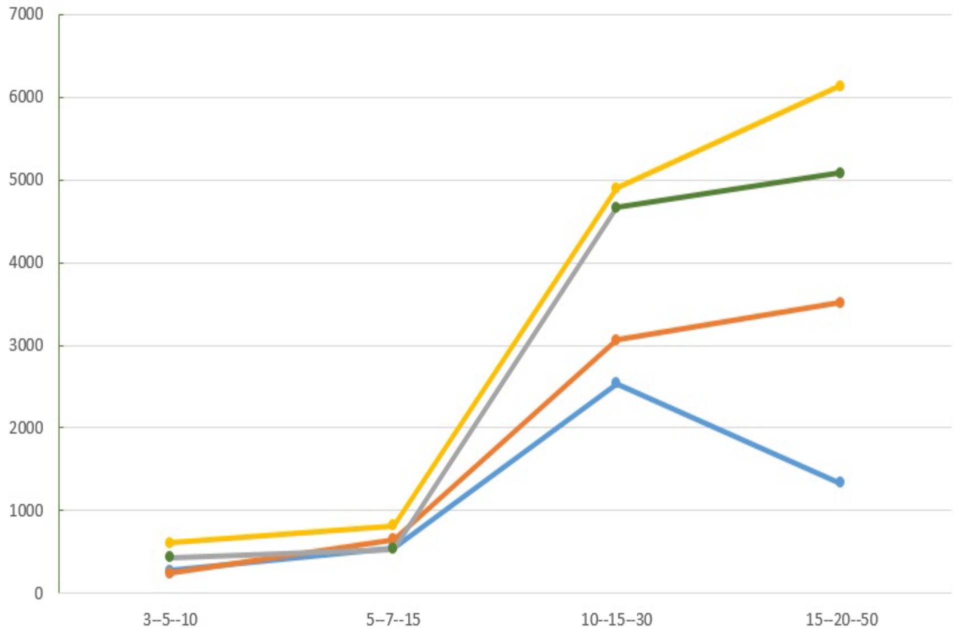
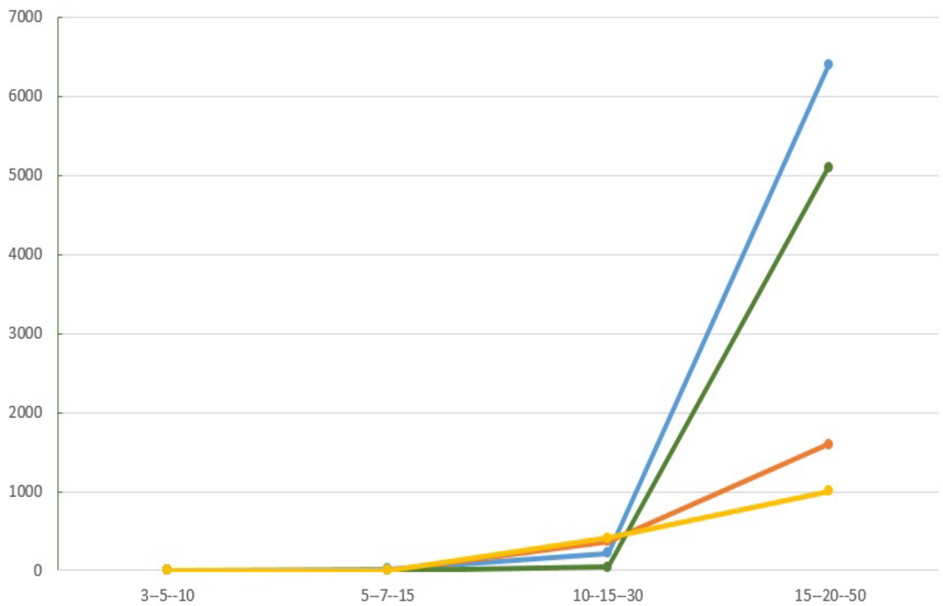


Figure 4 The average of the third objective function in problems with different sizes (see online version for colours)



4.1 Analysis of figures

As the figures show whatever the number of different sizes of problem increases, the amount of the objective function also increases because fixed costs, and thus the distance travelled by each vehicle increases, therefore, shipping costs increase.

According to Table 3, the results of model solving in this software, the exact resolution time is greatly increased. Therefore, using the exact approach can be only used for small-sized model, and with increasing size, the precise approach loses its efficiency. In other words, in the real world, it's not possible to use accurate approaches, because solving the model requires a lot of time.

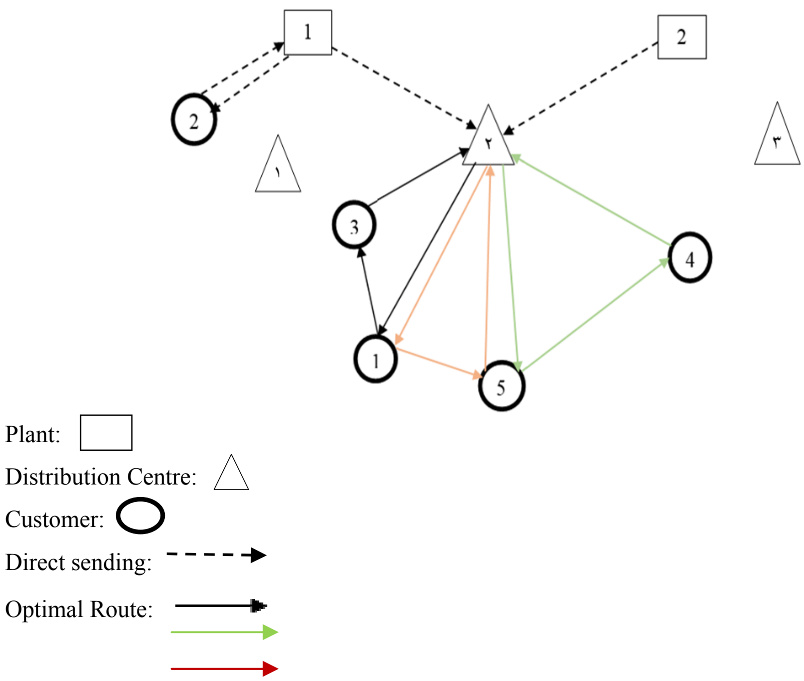
Table 3 Best solutions for objective functions

The best solutions by software GAMS	
1094797 8.275	The first objective function value
1701563.135	The second objective function value
6131.887	The third objective function value
2.886	Computing time

4.2 Graphical view of optimal routes to move vehicles:

In Figure 5, the optimal solution and graphic view of the vehicle movement is depicted:

Figure 5 Graphical view of vehicle movement (see online version for colours)



4.3 Sensitivity analysis

In this section, sensitivity analysis has been used to demonstrate the correctness of modelling and to determine the function is more sensitive to change in which sensitivity parameter. To do this, at first we identify parameters of the problem that can be changed their values and, we assume that the other parameters are constant and examine the effect of that change on the model.

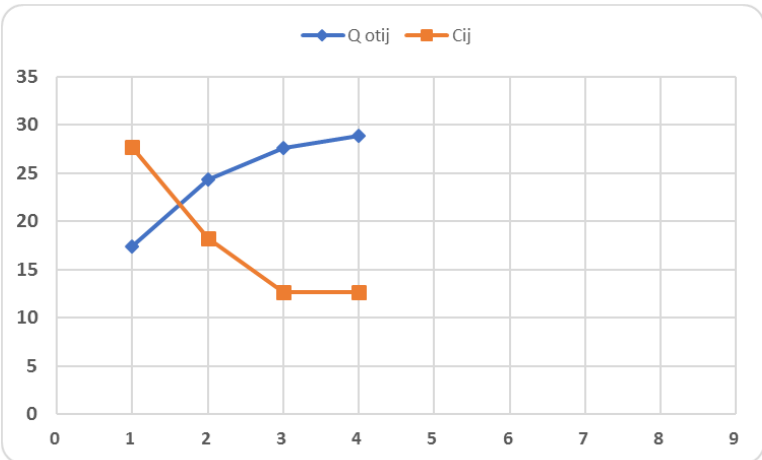
Table 4 shows that with increasing the parameter C_{ij}, the value of target function decreases, and with increasing Q_{otij} parameter, the value of objective function increases. Therefore, in this study, since our objective is to minimise target objectives\ and increase quality, then the parameters C_{ij} and Q_{otij} correctly represent this point.

Table 4 Percentage progress table for the value of the target function for the two parameters C_{ij} and Q_{otij}

%Progress	*Cost* (C_{ij})	*Quality* (Q_{otij})
25%	27.6630	17.3830
50%	18.2650	24.3440
75%	12.6780	27.6510
100%	12.6780	28.8400

Figure 6 shows that with increase of parameter C_{ij}, the value of the objective function decreases and with increase of Q_{otij} parameter (quality), the value of the target function increases.

Figure 6 The chart of increase and decrease in the value of objective function by influencing the parameters C_{ij} and Q_{otij} (see online version for colours)



4.4 Contributions

The issue of riding vehicles with fuzzy time windows is also one of the issues that can be developed for future research. This issue in multilevel mode, service life, fuzzy demand, and customer change over time can be investigated as future research. The results of this research can be used for distribution companies (in various industries) as well as mass producer companies that are responsible for distributing their goods nationwide. Using this template while reducing the organisation's costs from the point of view organising the order system will increase customer satisfaction and timely delivery of the goods to them.

5 Conclusion and future work

Reducing costs and increasing service levels are considered as the most important factors in today's market competition factors. In this regard, supply chain management (SCM) is considered in the framework of a systematic system, and in order to reduce the cost and increase the level of service in providing product and service to the customer among members. This study develops a mathematical model in the vehicle locating-routing problem in the three-tier supply chain, with a time window for customers aimed to minimise total system costs, including shipping, maintenance costs, etc. As well as balancing distribution costs and increasing quality. Regarding the results of MILP multi objective mathematical model solving, it can be argued that the proposed model by considering parameters, decision variables and problem constraints, simultaneously can design an integrated supply chain network, along with facility routing and determining transport policy design. According to studies conducted in this study, it will be clear that this model by considering all of these considerations simultaneously can be great help in solving problems. The results of mathematical model solving of this study, which is written in the BOM software, that desired result can be achieved with minimum cost and having limited amount of facilities movement of vehicles without confusion and waste of time and desired outcome of hand found. The results of MILP model solving in this software showed that with increasing the size of the problem, the exact solution time is greatly increased. Therefore, using the exact approach is the only responsive model of a small size, and with increasing size of the model, the precise approach only can be used for small model, in other words, in the real world, accurate approaches can't be used, since the solution of the model requires a lot of time.

Future research is recommended in the following aspects.

- The modelling solving is proposed using meta-heuristic algorithms to solve large size samples and samples in the real environment.
- The results of this study can be used for explanatory companies (in various industries) as well as mass-producing companies which are responsible for distributing their products throughout the country. Applying this pattern while reducing the organisation's costs from the point of view organising, in terms of organising the orders system will increase customer satisfaction and timely delivery of goods to them.
- One can add another operational limitation, such as impossibility of moving some vehicles on some routes, to the problem.
- Development of the problem for a situation where some of the parameters of problem (coefficient of consumption, fraction times, etc.) follows from the probability distribution functions.

- Developing the problem for a situation where each vehicle can perform both distribution operations and operations to collect the required materials and components.
- Development of the problem for a situation where the central distribution warehouse has a limit on the amount of inventory.

The results obtained in this work are comparable to or even better than that obtained in the literature. It is shown that the method proposed is simple and of high computational efficiency. It is shown that the new method is effective and simple for design of regional supply chains and solving VRP. The results of the case studies obtained in this paper are close to those obtained in the literature, even equal to the optimal solutions.

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