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A green closed loop supply chain design using queuing system for reducing environmental impact and energy consumption

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A B S T R A C T

Due to increased environmental impacts and their important role in human life, reduction of impacts made by human has attracted more attention, recently. Green supply chains are among the most effective issues related to environmental impacts and increased number of studies in this area verifies this opinion. Transportation fleets transfer products between supply chain's centers and are one of the important factors which increase environmental impacts. Transportation fleets which transfer products between supply chain's centers are one of the important factors which increase environmental impacts while transferring products between centers and waiting in loading queue. Decreasing environmental impacts which are created by transportation fleets, from this point of view, is not investigated comprehensively in forward and reverse logistic supply chains. In order to deal with this gap, in this article a green supply chain with forward and reverse logistic consideration is designed and queuing system is used to optimize the transportation and waiting time of transportation fleets' network. This optimization model will lead to the reduction in environmental impacts. Our network consists of supplier, production system, distribution center, repair center, recycling center, disposal center, and collection center. Returned products from customers are collected in the collection center and transferred to other centers based on their type. Transportation fleets in the network are assumed to be customers of loading system in each center where each of these loading systems has a multi-server queuing system with finite sources. It is assumed that a sufficient number of servers are available in unloading centers, therefore, no queue will exist there. The proposed model will reduce the created environmental impacts and energy consumption of transportation fleets by determining loading, unloading and production rates, which affect waiting and transportation time. A numerical example is discussed for the NLP model in small size and solved with the exact methods. In addition, a meta-heuristics approach is employed to solve the large size of problem. Finally, the sensitivity analysis is performed to investigate the effects of change in parameters on model's decision variables and objective function.

1. Introduction

Supply chain management, which has been considered as a process for converting raw materials to final products and delivering products to customers, can bring competitive advantages for a business (Christopher, 2016). Green supply chain, which specifically concentrates on designing an environmentally friendly supply chain, can guarantee achieving an aspect of sustainability and competitive advantages. Green supply chain management can reduce wastes, costs and also improve the relationships between the commercial partners and their leader companies (Aziziankohan et al., 2017). As a result of increase in customer's demand, higher rate of production requires more transportation fleet in network that causes more environmental effects. Environmental effects refer to different concepts such as pollution, noise, traffic, congestion, etc. (Fuglestvedt et al., 2008; Pereira et al., 2010; Rodrigue et al., 2016). This has been the concentration of most studies on reducing environmental impacts of production and distribution networks besides providing customers' demand by designing green supply chains. Furthermore, consideration of reverse logistics for valuing returned products or their appropriate destruction can lead to a green network (Zarbakhshnia et al., 2019). On the other hand,

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because transportation fleets transfer products between network's centers, and spend some time in different centers for loading or unloading, they are certainly one of the factors for energy consumption and environmental impact creation. Therefore regarding to Golicic et al. (2010) fleet management will have positive effect on energy efficiency and will reduce environmental impacts caused by fleets. Regarding to the fact that there is usually limited capacity for loading, they must spend some time waiting in queue for loading and it may cause more energy consumption and environmental impact (Aziziankohan et al., 2017). It can be assumed that for unloading no queue will be formed but assuming queue for loading systems is rational. Therefore, a green supply chain with reverse logistics consideration by assuming forming queue in loading centers is investigated in this article and queuing system models for reducing energy consumption is employed which makes the presented model closer to real world assumptions. It is clear that by managing waiting time for transportation fleets, environmental impacts can be reduced and this is what happens in real world. In the previous studies, green supply chain is not investigated from the point of view that waiting time in loading queue can also increase environmental impacts. Moreover, all of the conditions for a reversed product from a customers such as recycle, repair, remanufacture and considering products as waste are investigated in this article. Management of transportation fleets in supply chain has not been studied in the previous studies as comprehensively as did in this paper. Transportation fleets are assumed as customers of queuing system entering different centers for loading and receiving service while after loading products transportation fleets transfer them to other centers. It is obvious that less waiting and transportation time will cause less energy consumption (Aziziankohan et al., 2017). In addition, They stated that waiting time and transporttion time will increase environmental impacts and they assumed that number of transportation fleets in each section of supply chain is limited and is specified. However, in this paper, this limitation is not investigated and by considering the limitation of transportatin fleets which are assumed as customers of system, management of fleets should lead to a reduction in environmental effects. This explanation formed our research's question and in this article, we address the available literature gap by exploring the research question: Can consideration of network's transportation fleets as the customers of queuing system with finite source decrease the amount of created pollution by transportation fleets?

Moreover, it is essential to remind that in each supply chain there are two kinds of flow for materials and products. Forward supply chain determines forward flow of materials and products in a network. In this kind of supply chain after providing raw materials, intermediate and final products are produced through passing different supply chain's centers and at last final products are delivered to customers by distribution centers (Kannan et al., 2010). There is also a reverse flow of products from customers to supply chain's centers, which is attracting more attention in recent researches. Reverse logistic explains that products can return from customers in order to be disposed, recycled, reused or remanufactured Mishra et al. (2012). In our network, besides considering forward flow of materials from the supplier to the production system and then to distribution center and customers, reverse logistic is investigated in supply chain's design by considering return of products from customers to the collection center for transferring to recycle center, repair center, disposal center and production system. In fact, by simultaneous consideration of forward and reverse logistics, a closed loop supply chain is presented in the article.

In our presented model, we address the research gap by contributing the literature in following points. First, a queuing system for a green supply chain with reverse logistic consideration in a more comprehensive form than the previous research is employed and a different attitude toward green supply chain and reverse logistic for energy reduction is considered. Second, green supply chain monitoring with reverse logistic in terms of congestion is discussed. In fact, in this supply chain transportation fleets which transfer products between different centers of a supply chain have to wait in loading queue for receiving services and this created queue in loading center cause an increase in waiting time and transportation time between supply chain's centers such as recycle center, remanufacture center, production system and so on. It will leads to increase in environmental impact and energy consumption. Third, a G/M/S queuing system with a finite source is assumed for transportation fleets in loading systems (Bunday and Scraton, 1980; Nelson, 2013) and to the best of our knowledge, this is the first time this kind of queuing system is employed in this article for a green supply chain. It is essential to remind that notations used for a G/M/S queuing system indicate that the entrance time has general distribution (G), servicing time has exponential distribution (M) and there are S numbers of servers for providing service (S) (Ghosh, 2012). Fourth, transportation fleets are assumed as customers of loading systems in each center but no queue will be formed in unloading system due to the sufficient number of servers. At last, by considering S servers in each loading center a comprehensive model can be achieved. Therefore, to achieve a green design for supply chain we used queuing system for our optimization problem. In fact, by specifying loading, unloading and production rate amount of created environmental impact can be optimized.

This paper will be organized as follows. In the first section, we explain the necessity of designing a green closed supply chain with queuing systems consideration that leads to the environmental impact and energy reduction. Then, in section 2 relevant literature is reviewed and in section 3 our research methodology is discussed and a description of problem besides model formulation is explained. A problem is solved in small and large size with exact and meta-heuristics methods in section 4. Results are indicated section 5 and also a sensitivity analysis is performed in this section. Finally, conclusions are discussed in section 6.

2. Theoretical background and development of hypothesis

Green supply chain management which especially focuses on environmental aspect of sustainability, can be influential on reaching a sustainable supply chain (Sarkis et al., 2011). Environmental concerns have increased due to the diffusion of industrial environmental impacts, which threaten human beings and their environment. In order to decrease destructive effects of industrial productions, manufacturers are required to consider reverse logistic beside typical forward one. Green supply chain management mainly focuses on environmental aspects of designing a supply chain which is one of the aspects of a sustainable supply chain (Guang shi et al., 2012). Improving environmental performance is the main application of green supply chain management (Sellitto, 2018). Green supply chain management can also decrease environmental impacts, in supply chain (Darnall et al., 2008). Environmental assessment of different supply chain's centers such as supplier, distribution center, customers and so on is one of the green supply chain management applications (Sellitto et al., 2012). Waste and environmental impacts reduction, can be investigated by measures which are provided through environmental assessments (Darnall et al., 2008). Raw materials supply, internal logistics, conservation, external logistics, marketing and after sales services are aspects of green supply chain management (Haw-Jan and C., 1995). Green supply chain management which integrate environmental concerns with supply chain management, control environmental impacts of products in its life cycle besides reducing supply chain's energy consumption (Zhu et al., 2017). Green supply chain management includes green design as an approach for increasing product quality while considering environmental aspects of a product. Environmentally conscious design (ECD) and life cycle assessment/analysis (LCA) are dimensions which must be considered for achieving a green design (Glantschnig, 1994). There are five main practices which result in achieving green supply chain management. They include eco-design practices (ECO), customer cooperation about environmental issues (CC), investment recovery (IR), green purchasing (GP) and internal environmental management (IEM) (Liu et al., 2018). Eco-design is defined as consideration of environmental issues in designing products to reduce undesirable environmental impacts in product's life cycle (Serhan and Yannou-Le Bris, 2018). Managerial and operational practices are categories of eco-design practices. Managerial practices investigate the availability of resources in product life cycle and controlling the performance in life cycle. Concentration on reducing energy and hazardous materials is in the category of operational practices (Sihvonen and Partanen, 2017). Although replacing hazardous materials or processes by less hazardous ones is an approach for achieving a green network, it can sometimes be undesirable if it leads to consuming scarce resources (Srivastava, 2007). Waste management is also another concept in green supply chain management. Petljak et al. (2018) state that waste management which deals with amount of created waste in supply chain, is mainly affected by green purchasing and management of cooperation with suppliers while logistics can also affect it. To specify suitable waste centers' location and policy evaluation for urban waste management, a decision support system was proposed by Haastrup et al. (1998). Arena et al. (2003) used the life cycle assessment for solid waste management options. Finally Sihvonen and Partanen (2017) declare that remanufacturing, environmental design, and efforts for waste reduction are among the most important environmental practices. We reviewed the main concepts about green supply management and then researchers' practices about designing green supply chain will be studied.

Shaw et al. (2016) use benders' decomposition method for the problem of designing a green supply chain, which investigates optimization of cost and greenhouse gas emission. Miranda-Ackerman et al. (2017) developed a forward supply chain and used a life cycle assessment approach in their article. They focused on cost minimization for their case study and employed genetic algorithm to solve the model. Petljak et al. (2018) studied green supply chain management in food retailing. Effects of green in-store activities and green supply chain approaches are evaluated on economic and environmental functions. Yu and Solvang (2018) presented a MILP model to design a green supply chain. Weighted sum and epsilon constraint method is used for the optimization of the designed bi-objective model and finally the trade-off between objectives is studied.

Reverse logistics concentrate on enhancing environmental, economic and social dimensions of a supply chain (Carter and Lianeeaston, 2011) while, reduce the destructive effects of waste generation caused by industrial practices. Reverse logistics lead to achieving environmental objectives by legislation which is affected by consumers and government's concerns about environmental issues recently. Reverse and direct logistics are different in the direction of products transshipment. In direct logistics, products are conveyed toward customers while in reverse logistics products are conveyed from customers. Practices which are evaluated in reverse logistics include identifying wastes, collecting, sorting, compacting, storing, recollecting, transporting, delivering and value recovering. Control over the flow of materials from the end point of supply chain which is consumption or disposal center to its beginning, form the concept of reverse logistics. Recovering the remaining value of products or specifying suitable place for disposal is the goal of reverse logistics (Sellitto, 2018). Reverse channels are a main concept in reverse channels which is comprehensively discussed in our article. Reuse, recycling, remanufacturing, disposal and energy recovery are the main reverse channels which must be investigated in reverse logistics. Each of these reverse channels has a specific definition in the related literature. For reuse, materials can be used several times before performing minor repairs. and repairs will not change the main structure of materials (Sellitto et al., 2017). Recycling indicate materials flow to cooperatives for classifying, separating and processing (Rahimifard et al., 2009) and wastes that are created in this processes are used as feedstock. In remanufacturing process materials requires remarkable reformation and repaired parts can be used for manufacturing new products (Ongondo et al., 2011). Another reverse channel refer to the process for dealing with the final disposal and this process can include landfill, incineration and energy generation (Hung lau and Wang, 2009). Reverse logistics which is employed in our article is also studied in the practices which are reviewed below. Nagurney and Toyasaki (2005) concentrate on reverse logistics to achieve green marketing. Integration of forward and reverse supply chain, which forms the concept of closed loop supply chain, has gained attention in the literature. Min et al. (2005) presented a multi-echelon, multi-product closed loop supply chain, which is a nonlinear programming model and considered, return of products. Inderfurth (2005) investigated a product recovery system and analyzed production policy while they assumed demand to be deterministic. Sheu et al. (2005) studied a green supply chain and presented a multi-objective optimization model for integrated and reverse logistic. Government's policy as the given subsidy has been investigated in the article. A case study in Taiwan is also discussed for proving mathematical model. Millet (2011) evaluated reverse logistics structures based on the treatment activities' location. Dwivedy and Mittal (2012) performed a case study in India for waste electrical and electronic equipment supply chain. Subramonian et al. (2013) worked on the decision-making structure using AHP method for a remanufacturing system and surveyed original equipment manufacturers. Nikolaou et al. (2013) integrated sustainability concepts with reverse logistic. In fact, social responsibility criteria are considered in their reverse logistic model. In another research, Bai and Sarkis (2013) studied operational and strategic aspects of flexibility in reverse logistic. Govindan and Soleimani (2017) referred to a general framework for closed loop supply chain in their review article. In that structure, raw materials in forward logistic are transferred to processing center and then assembly center. Then, distributers or retailers convey products to consumers. In the reverse logistic, returned products from customers are transferred to repair, recondition, remanufacture or recycle centers. At last, wastes from each of the centers in the network are sent to disposal center.

In each supply chain, there are two main kinds of decisions named strategic and tactical ones. Özceylan et al. (2014) considered both of these decisions for a closed loop supply chain in their article. Then here we review the studies which integrate the concept of green supply chain and reverse logistics. Soleimani and Kannan (2015) employed particle swarm optimization meta-heuristic algorithm for a closed loop supply chain in order to evaluate model applicability for different sizes of problem by. Zohal and Soleimani (2016) investigated a green closed loop supply chain that concentrate on economic and environmental objectives and used meta-heuristics approaches to solve the model. Giri et al. (2017) proposed a closed-loop supply chain with two dual channels. Third party logistics and e-tail channels are responsible for returning the used products in the model. Decisions about pricing and returned products are investigated under different scenarios. Fazli-Khalaf et al. (2017) designed a bi-objective green closed loop supply chain, which minimizes undesirable environmental effects of supply chain, and supply chain costs. Scenario-based stochastic programming and hybrid robust fuzzy stochastic programming are employed in the article, in order to discuss disruption and uncertainty of parameters. Rad and Nahavandi (2018) designed a multi-objective MILP model for green closed loop supply chain. Minimization of economic and environmental objectives and maximization of customers' satisfaction are investigated in the model. Quantity discount is a motivator in that model for buyers. Sensitivity analysis is conducted for this multi-echelon, multi-period, multi-product closed loop supply chain. Ghomi-Avili et al. (2018) considered effects of disruptions in supplier for designing a competitive green closed loop supply chain. They used the fuzzy approach to deal with the uncertainty of demand that originates from dependency of demand to offered price to customers. The bi-objective model is solved by epsilon constraint method for a case study. Jabbarzadeh et al. (2018) considered risk and disruption in their proposed model for a closed loop supply chain, which minimizes costs when specifying facility location and transshipment quantities. A real case study in Iran is conducted for model in order to evaluate model's capability. The above researches concentrated on designing green and closed loop supply chains but they did not try to use queuing systems in their presented network for reducing environmental impacts. So now we review the works that employed queuing systems in their supply chains. Today customers value time more than they ever did, due to increase in life's speed. Consequently, it is essential for manufactures to deliver products to customers on time (Hum et al., 2018). Queuing system can help us in supply chain management by improving the possibility of fulfilling customers' orders within a specific lead-time. In these models, the applicant, human or other things, are considered as customers and the service providers are known as servers. Production systems, storage and transportation systems, communication systems and information processing systems are practical fields which queuing system can be used for in terms of design, capacity and control (Adan and Resing, 2015). Here some of recent researches, which used queuing system as a tool for modelling their problems, are reviewed. Vahdani et al. (2012) propose an M/M/c queuing model under uncertainty for a closed loop supply chain. Zahiri et al. (2014) proposed a bi-objective model that incorporates cost and time minimization. In order to minimize waiting time in organ transplant transportation network, queuing system is investigated in the model. A case study is discussed for the problem and meta-heuristics approach is employed for solving the large size of problem. Vass and Szabo (2015) proposed their queuing model in health area. They tried to minimize average waiting time for patients by queuing system, so that patient's satisfaction will increase. The results of their study can help us to understand the magnitude of the broader problem, as well as the relationship between resources and waiting times, and to provide a method for understanding and monitoring performance. Vahdani and Mohammadi (2015) used queuing system in their bi-objective optimization model. Multi-server queuing system is considered for the closed loop supply chain and the waiting time in queue as well as total costs of supply chain is minimized. Moreover, different kinds of uncertainty are studied for problem besides presenting a meta-heuristic approach for solving the model. Saeedi et al. (2015) utilized an M/M/1 queuing system in an MINLP model, which is proposed for a closed loop supply chain network. Specifying capacity of facilities by considering cost of supply chain including queuing costs and fixed costs is discussed in the article. Zhalechian et al. (2016) developed a MOMINLP model for multi-period, multi-product closed loop supply chain by uncertainty consideration. Remanufacturing facilities are discussed in the model by presenting an M/M/c queuing system for calculating waiting time of transportation fleets. Stochastic-possibilistic programming method and a modified game theory approach are used to deal with assumed uncertainty of model. Zhang et al. (2016) used queuing system in their model for planning under uncertainty besides considering customers' demand and routing problem in their model. In fact, a new hybrid approach, which consists of methods for dealing with uncertainty and queuing system, is used for solving the bi-objective model. Ding et al. (2016) proposed a queuing system model for traffic congestion optimization in a wireless sensor network. First, they constructed a queuing network model for specifying nodes' congestion. Then an optimization routing algorithm is proposed. Aziziankohan et al. (2017) proposed a model for green supply chain management and they minimized traffic congestion by queuing system. Their findings show that the suitable assignment of transportation fleet, using queuing system in a closed-loop network to reduce queue length and handling congestion can cause reduction in energy consumption by optimizing transportation and waiting times in a green supply chain. Rahimi et al. (2016) used a M/M/c/K queuing model for solving a new bi-objective model for a Hub location problem under uncertainty and cosidered congestion in the hubs. Objective function minimizes total transportation cost and transportation time between each network's nodes. The aforementioned articles employed different queueing models in their presented networks but they did not combine concepts of queuing systems and green supply chain. Most of these practices did not used queuing system in order to reduce environmental impacts. Aziziankohan et al. (2017) which used queuing system in their supply chain for reducing environmental impacts and energy consumption by transportation fleets, assumed there are limited and specified number of fleets in each section of supply chain. Therefore, in order to deal with their research's limitation we did not consider limited number of fleets in our network and in this article we employied queuing sytems in our presented supply chain in order to reduce environmental impacts. Aziziankohan et al. (2017) did not consider the customers of queuing system as a constraint in the system. Customers are interpreted as the limited number of transportation fleets in each part of supply chain and this model is assumed as the queuing system with finite source. To the best of our knowledge this is a new approach for achieving a green supply chain through reducing environmental impacts by using the concept of queueing system in loading queue.

Hypotheses considered in modelling our presented closed loop supply chain are as follows:

Hypothesis 1. By increasing the number of transportation vehicles, length of queue, waiting time in queue and unloading rate and loading rate will increase for achieving optimization and reducing energy consumption.

Hypothesis 2. Increasing the demand causes amount of created environmental impact and energy consumption to increase.

Hypothesis 3. Increasing the number of servers in loading centers leads to reduction in loading rate. However, after a point, reduction in required time for returning to loading center and increase in entrance rate will cause loading rate to increase.

Hypothesis 4. It is expected that with the increase in capacity of transportation fleets, first length of queue and waiting time will be increased and then because of transferring more products to other centers, providing demand becomes faster and less transportation fleets will be required and therefore after a point length of queue and waiting time will be decreased.

Hypothesis 5. By increasing the rate of returned products from customers, more queue for loading will be formed in repair center, recycle and collection center which can increase the amount of energy consumption. However, because of the reduction in the requirement to raw materials and possibility of providing part of demand through recycling or repairing the returned products, energy consumption can be reduced. Therefore, a fluctuation can be possible in objective function for optimum point of which we are searching.

3. Methodological concerns

3.1. Problem description

To achieve a green supply chain design, which leads to environmental impact reduction and being environmentally friendly, queuing system, is employed in loading systems of our presented model. Our purpose in this article is to determine loading, unloading and production rates in order to optimize transportation time and waiting time for transportation fleets in loading systems. Therefore, the amount of created environmental impact by transportation fleets and consumed energy will be optimized. Reverse flow of products from customers to collection center and then to different sections of supply chain is studied in the model. This reverse logistic besides forward flow of materials and products constitutes a closed loop supply chain (Kazemi et al., 2018). Considering backward flow of products from end-users, distribution center and manufacturing center in a supply chain, add the concept of reverse logistics to conventional supply chains. Therefore reverse logistics beside ordinary forward flow of materials constitute a closed loop supply chain.

As it is indicated in Fig. 1, the designed network in this article consists of supplier, production system, distribution center, collection center, repair center, recycle center and disposal center Govindan and Soleimani (2017) Raw materials are provided through supplier and then are transferred to production system by transportation fleets. Fig. 2 illustrates that a queue will exist in loading systems in each center (for example A) (Azizankohan et al., 2017). However, in unloading systems in each center (for example B), due to the sufficient number of servers no queue will be formed. Then, final products are transferred to the distribution center for delivering to customers for providing their demand. Production rate in production system is equal tor_p and probability of producing intact products in production system is equal to a. Therefore, production rate of intact and waste products in production system equals to r_p(a) and$r_p(1-a)$, respectively. When returned products from customers are transferred to collection center for specifying their applicability, reverse logistic initiate and our closed loop design forms (Srivastava, 2007). Collected products in collection center are categorized into 4 groups (Mishra et al., 2012; Franchetti et al., 2017). Products are reusable with probability P_1 and are returned to production system. They are repairable with probability P_2 and are returned to repair center while they can be recyclable with probability $P_3$and are transferred to recycle center. P_4 percent of products are waste which are transferred to disposal center. In repair center r_1 percent of products are converted into products with new products quality and are transferred to distribution center while $(1-r_1)$ percent of products are transferred to disposal center. Similarly, in recycle center r_2 percent of products are transferred to production system while $(1-r_2)$ percent are transferred to the disposal center.

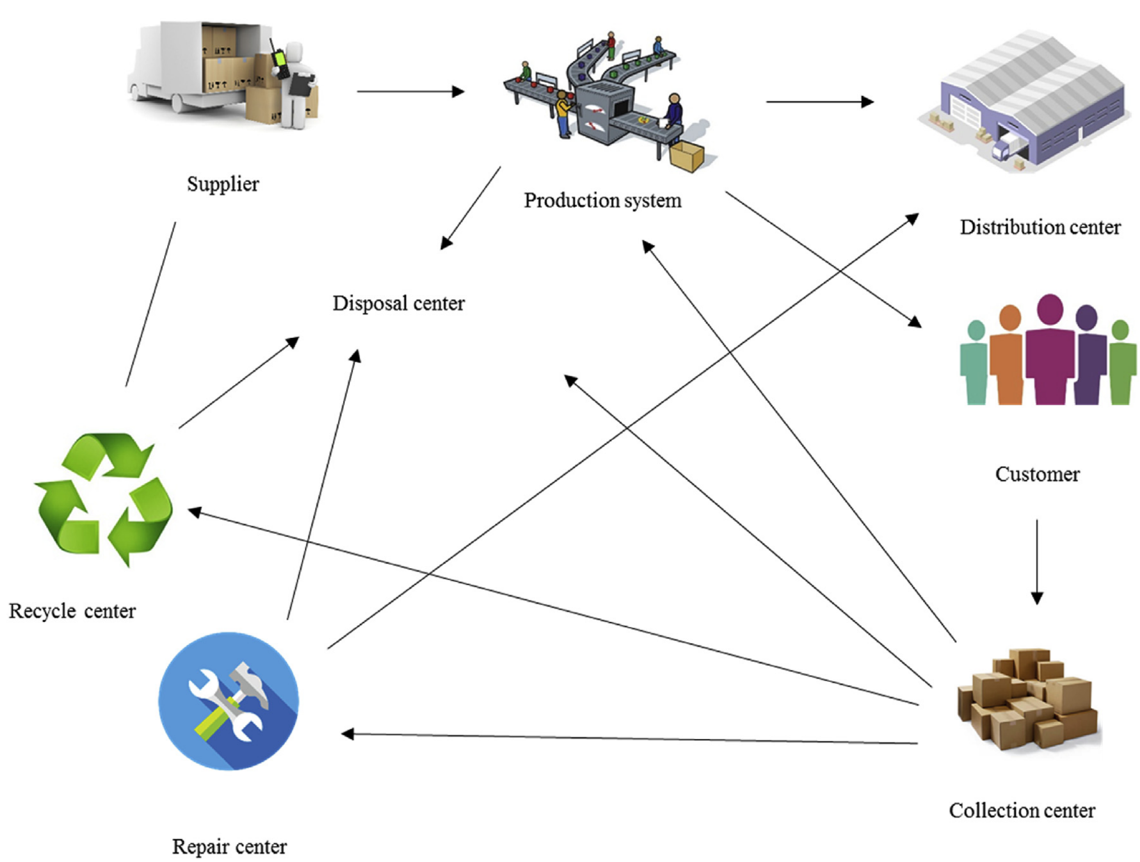


Fig. 1. Structre of proposed colesd loop supply chain.

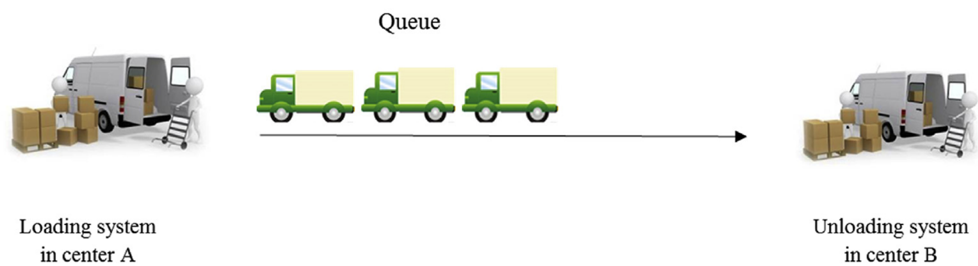


Fig. 2. Structre of queue in loading systems.

3.2. Assumptions

The following assumptions are considered to formulate the model:

1. A G/M/S queuing system is assumed in each supply chain's centers. After loading in each center, transportation fleets go to other centers and after unloading, they must return to the first center. Therefore, the time required for each transportation vehicles is the integration of time for going, unloading and returning. The time for unloading in each center has a general distribution. Total time for going and returning has *G*(general) distribution. Therefore, the required time for entering center, loading and then leaving the center will have general distribution. Time for loading has exponential distribution.
2. In unloading centers, we assume that there are a sufficient number of servers and no queue will exist. Time required for unloading in each center has *G* distribution.
3. Transportation time between the two centers is stochastic and has a general distribution.
4. Inspection time in collection center is assumed negligible.
5. Products collected in collection center are categorized into reusable, repairable, recyclable and waste products (Mishra et al., 2012; Franchetti et al., 2017)
6. It is assumed that in repair center and recycle center, queue will not be formed. Even if we assume that a queue will form, in statistical equilibrium, arrival rate and departure rate will be the same.
7. Disposal center has the maximum capacity (Kannan et al., 2010).
8. Products, which are specified as reusable ones in collection center, can be transferred to manufacture and converted into final products (Mishra et al., 2012). Each unit of reusable product can be converted into one unit of final product.
9. Reusable products are converted into intact products with probability a.
10. Loading rate in each center is equivalent for all of its loading systems.
11. Products are delivered to customers in distribution center.
12. Returned products are transferred to the collection center (Srivastava, 2007).
13. Three kinds of transportation fleets are defined in this article. Vehicles with high capacity are used in routes between supplier and manufacture. Low capacity transportation fleets are allocated to routs leading to disposal center and in other routes; vehicles with medium capacity are used.
14. Since constructing each loading center results in high expenses for a center, each system decides to have loading system up to the number of its customer which is equivalent to the number of transportation fleets. For example, if we consider NV number of transportation fleets in a section and c number of loading servers$(c < NV)$, $c - NV$ number of servers will always be idle. Besides, existing more than NV number in each section of loading systems will not cause reduction in waiting time, departure rate and transportation time. In these situations, whenever a customer arrives, a server is ready for servicing with the rate of $\mu_n = n\mu$. When the number of servers is more than the number of customers, service rate will not increase comparing the situation in which number of servers is equal to that of customers. Therefore, the maximum amount of service rate is$NV\mu$. Consequently, this increase in the number of servers will not lead to decrease in system density and will not change steady state probabilities. So, according to $L = \sum_{n=0}^{NV} n\pi_n$, L will not change with the increasing number of servers to more thanNV. At last, this increase will not reduce waiting time, entrance rate and departure rate$(NV - L)\lambda$. In this situation each system decides to have servers less than or equal to the number of customers and does not have idle servers. Therefore, in this article it is assumed that $NV_{ij} \geq S_{ij}$ and it will make a G/M/1 queuing system in each layer of network.
15. Each unit of products, which are returned from recycle and collection center, can be converted into one unit of product.

3.3. Model formulation

In each loading system, a G/M/S//M queuing system is considered. NV indicates the number of transportation fleets between loading centers and unloading centers, which are customers of queuing system. In each loading center, transportation fleets must transfer items to another center and then return after unloading. Therefore, the required time for each vehicle for going and returning equals to the required time for going, unloading and then returning. It is assumed that the unloading time in center j have general distribution with average of$1/\mu'$. Moreover, required time for going to center j for unloading from center i and then returning have general distribution with average of$1/T_{ij}$ and $1/T_{ji}$,respectively. So, the time for going to center j from center i and then returning to center j after unloading, has general distribution and is calculated by equation (1)

$$\frac{1}{\lambda_i} = \frac{1}{T_{ij}} + \frac{1}{T_{ji}} + \frac{1}{\mu'_j} \tag{1}$$

According to Bunday and Scraton (1980) limiting probability for the number of customers in a system, for G/M/C//M and M/M/C//M queuing systems, when vehicles or customers are independent of the source, is equivalent and is just dependent on the average time that each customer spends in the source after receiving service. *C* number of servers considers these kinds of queuing systems mostly in maintenance systems where M number of machines receive maintenance services. In these models, $1/\lambda$ indicates the average time for a vehicle that spends in source or is in run state after receiving service. In this article the required time for returning to a center after departure from it is equivalent to the time, which customers spend in source in the aforementioned maintenance model. In this article, the average of this time, which means going to unloading center and then returning, is calculated by equation (1). Therefore, it is clear that loading system of this article is similar to maintenance model with a finite source where $1/\lambda$ is calculated by equation (1). Besides, regarding assumption of transportation fleets' independency, in order to use M/M/C//M formula for G/M/C//M queuing systems, it is assumed that there are sufficient number of servers in unloading centers and queue will not exist there. Therefore, transportation fleets go to unloading centers independently and after unloading, they return to loading centers. Moreover, according to Sztrik (2010), Little's result for a G/M/S queuing system with finite source indicate that when equation (2) is true then equation (3) will be as follow.

$$F_i(x) = F(x) \quad i = 1, \ldots, M \tag{2}$$

$$\lambda(M - L)W = L \tag{3}$$

In equation (2) $F_i(x)$ indicates the distribution function of time which machine or customer i spends in the source. Therefore, in this paper it is assumed that all of the transportation fleets and servers in unloading centers are the same. Condition of passes for going and returning of transportation fleets is assumed the same. Under this condition, it can be concluded that the required time for each transportation fleet spent in source or is in the run state that here means required time for going, unloading and returning, is equivalent for all of them, so equation (2) is applied here. Comparing equation (3) with Little's result according to Little (1961) which states equation (4), will illustrate that in a G/M/S//M system, $\overline{\lambda}$ is calculated by equation (5).

$$L = \overline{\lambda}W \tag{4}$$

$$\overline{\lambda} = (M - L)\lambda \tag{5}$$

Notations

Indices	
$\boldsymbol{i} = 1$	Supplier
$\boldsymbol{i} = 2$	Production system
$\boldsymbol{i} = 3$	Distribution center
$\boldsymbol{i} = 4$	Collection center
$\boldsymbol{i} = 5$	Repair center
$\boldsymbol{i} = 6$	Recycle center
$\boldsymbol{i} = 7$	Disposal center
Parameters	
$\boldsymbol{a}$	Probability of producing intact products in manufacture
$\boldsymbol{P}_1$	Probability which indicate collected product in collection center be reusable
$\boldsymbol{P}_2$	Probability which indicate collected product in collection center be repairable
$\boldsymbol{P}_3$	Probability which indicate collected product in collection center be recyclable
$\boldsymbol{P}_4$	Probability which indicate collected product in collection center be disposable
$\boldsymbol{r}_1$	Probability of transferring products to distribution center after repair center
$\boldsymbol{r}_2$	Probability of transferring products to manufacture after recycle center
$\boldsymbol{cv}$	Capacity of each transportation vehicle (medium capacity)
$\boldsymbol{cvv}$	Capacity of each transportation vehicle (low capacity)
$\boldsymbol{cvvv}$	Capacity of each transportation vehicle (high capacity)
$\boldsymbol{C}$	Amount of environmental impact produced per unit of transportation time
$\boldsymbol{r_s}$	rate of transferring raw materials to supplier
$\boldsymbol{r_d}$	rate of demand in distribution center
$\boldsymbol{r_e}$	Rate of returning products from customers to collection center
$\boldsymbol{r_{dis}}$	Maximum disposal rate in disposal center
$\boldsymbol{s}_{12}$	Number of servers in center 1 for loading and then transferring products to center 2
$\boldsymbol{s}_{2j}$	Number of servers in center 2 for loading and then transferring products to center j j = 3,7
$\boldsymbol{s}_{4j}$	Number of servers in center 4 for loading and then transferring products to center j j = 2,5,6,7
$\boldsymbol{s}_{5j}$	Number of servers in center 5 for loading and then transferring products to center j j = 3,7
$\boldsymbol{s}_{6j}$	Number of servers in center 6 for loading and then transferring products to center j j = 2,7
$\boldsymbol{NV}_{12}$	Number of transportation fleets between center 1 and 2
$\boldsymbol{NV}_{2j}$	Number of transportation fleets between center 2 and j j = 3,7
$\boldsymbol{NV}_{4j}$	Number of transportation fleets between center 4 and j j = 2,5,6,7
$\boldsymbol{NV}_{5j}$	Number of transportation fleets between center 5 and j j = 3,7
$\boldsymbol{NV}_{6j}$	Number of transportation fleets between center 5 and j j = 2,7
$\boldsymbol{T}_{12}$	Total average time for transferring from center 1 to center 2 and returning
$\boldsymbol{T}_{2j}$	Total average time for transferring from center 2 to center j and returning j = 3,7
$\boldsymbol{T}_{4j}$	Total average time for transferring from center 4 to center j and returning j = 2,5,6,7
$\boldsymbol{T}_{5j}$	Total average time for transferring from center 5 to center j and returning j = 3,7
$\boldsymbol{T}_{6j}$	Total average time for transferring from center 6 to center j and returning j = 2,7
Decision variables	

(continued on next page)

(continued)

μ'_i	Unloading rate in center i i = 2,3,5,6,7
μ_{12}	Loading rate in center 1 for transferring to center 2
μ_{2j}	Loading rate in center 2 for transferring to center j j = 3,7
μ_{4j}	Loading rate in center 4 for transferring to center j j = 2,5,6,7
μ_{5j}	Loading rate in center 5 for transferring to center j j = 3,7
μ_{6j}	Loading rate in center 6 for transferring to center j j = 2,7
λ_{12}	Average time for a vehicle for returning to center 1 after departure from center 1 for going to center 2 in loading system
λ_{2j}	Average time for a vehicle for returning to center 2 after departure from center 2 for going to center j in loading system j = 3,7
λ_{4j}	Average time for a vehicle for returning to center 2 after departure from center 4 loading system for going to center j j = 2,5,6,7
λ_{5j}	Average time for a vehicle for returning to center 2 after departure from center 5 loading system for going to center j j = 3,7
λ_{6j}	Average time for a vehicle for returning to center 2 after departure from center 6 loading system for going to center j j = 2,7
W_{12}	Average waiting time for loading in center 1 and the transferring products to center 2
W_{2j}	Average waiting time for loading in center 2 and the transferring products to center j j = 3,7
W_{4j}	Average waiting time for loading in center 4 and the transferring products to center j j = 2,5,6,7
W_{5j}	Average waiting time for loading in center 5 and the transferring products to center j j = 3,7
W_{6j}	Average waiting time for loading in center 6 and the transferring products to center j j = 2,7
$L12$	Average number of transportation vehicles in center i for loading i = 1
$L2j$	Average number of transportation vehicles for loading in center 2 for transferring to center j j = 3,7
$L4j$	Average number of transportation vehicles for loading in center 4 for transferring to center j j = 2,5,6,7
$L5j$	Average number of transportation vehicles for loading in center 5 for transferring to center j j = 3,7
$L6j$	Average number of transportation vehicles for loading in center 6 for transferring to center j j = 2,7
LQ_{12}	Average length of queue for loading in center 1 for transferring to center 2
LQ_{2j}	Average length of queue for loading in center 2 for transferring to center j j = 3,7
LQ_{4j}	Average length of queue for loading in center 4 for transferring to center j j = 2,5,6,7
LQ_{5j}	Average length of queue for loading in center 5 for transferring to center j j = 3,7
LQ_{6j}	Average length of queue for loading in center 6 for transferring to center j j = 2,7
r_p	Total production rate
π^0_{12}	Idle probability of server for loading in center 1 for transferring products to center 2 n = 0, 1 …, NV_{12}
π^0_{2j}	Idle probability of server for loading in center 2 for transferring products to center j n = 0, 1 …, NV_{2j} j = 3,7
π^0_{4j}	Idle probability of server for loading in center 4 for transferring products to center j n = 0,1. …, NV_{4j} j = 2,5,6,7
π^0_{5j}	Idle probability of server for loading in center 5 for transferring products to center j n = 0, 1 …, NV_{5j} j = 3,7
π^0_{6j}	Idle probability of server for loading in center 6 for transferring products to center j n = 0, 1 …, NV_{6j} j = 2,7
π^n_{12}	Probability of existing n machine for loading in center 1 for transferring products to center 2 n = 1 …, NV_{12}
π^n_{2j}	Probability of existing n machine for loading in center 2 for transferring products to center j n = 1, 2 …, NV_{2j} j = 3,7
π^n_{4j}	Probability of existing n machine for loading in center 4 for transferring products to center j n = 1, 2 …, NV_{4j} j = 2,5,6,7
π^n_{5j}	Probability of existing n machine for loading in center 5 for transferring products to center j n = 1, 2 …, NV_{5j} j = 3,7
π^n_{6j}	Probability of existing n machine for loading in center 6 for transferring products to center j n = 1, 2 …, NV_{6j} j = 2,7

Equations

$$min\left((NV_{12}-L_{12})\lambda_{12}+\sum_{j=3,7}\left((NV_{2j}-L_{2j})\lambda_{2j}\right)+\sum_{j=2,5,6,7}\left(\times(NV_{4j}-L_{4j})\lambda_{4j}\right)+\sum_{j=3,7}\left((NV_{5j}-L_{5j})\lambda_{5j}\right)+\sum_{j=2,7}\left(\times(NV_{6j}-L_{6j})\lambda_{6j}\right)+W_{12}LQ_{12}+\sum_{j=3,7}W_{2j}LQ_{2j}+\sum_{j=2,5,6,7}W_{4j}LQ_{4j}+\sum_{j=2,7}W_{5j}LQ_{5j}+\sum_{j=3,7}W_{6j}LQ_{6j}\right)*(2C) \tag{6}$$

$$(NV_{12}-L_{12})\lambda_{12}*CVVV\leq r_s \tag{7}$$

$$(NV_{12}-L_{12})*\lambda_{12}*CVVV+(NV_{42}-L_{42})*\lambda_{42}*CV+(NV_{62}-L_{62})*\lambda_{62}*CV\geq r_p \tag{8}$$

$$(NV_{27}-L_{27})*\lambda_{27}*CVV\leq r_p(1-\mathrm{a}) \tag{9}$$

$$(NV_{23}-L_{23})\lambda_{23}CV\leq r_p\mathrm{a} \tag{10}$$

$$((NV_{23}-L_{23})\lambda_{23}+(NV_{53}-L_{53})\lambda_{53})*CV\geq r_d \tag{11}$$

$$(NV_{42}-L_{42})*\lambda_{42}*CV\leq r_e p_1 \tag{12}$$

$$(NV_{45}-L_{45})*\lambda_{45}*CV\leq r_e p_2 \tag{13}$$

$$(NV_{46}-L_{46})*\lambda_{46}*CV\leq r_e p_3 \tag{14}$$

$$(NV_{47}-L_{47})*\lambda_{47}*CVV\leq r_e p_4 \tag{15}$$

$$(NV_{53}-L_{53})*\lambda_{53}\leq(NV_{45}-L_{45})\lambda_{45}*r_1 \tag{16}$$

$$(NV_{57}-L_{57})\lambda_{57}CVV\leq(NV_{45}-L_{45})\lambda_{45}CV(1-r_1) \tag{17}$$

$$(NV_{62}-L_{62})\lambda_{62}\leq(NV_{46}-L_{46})\lambda_{46}r_2 \tag{18}$$

$$(NV_{67}-L_{67})\lambda_{67}CVV\leq(NV_{46}-L_{46})\lambda_{46}CV(1-r_2) \tag{19}$$

$$[(NV_{27}-L_{27})\lambda_{27}+(NV_{47}-L_{47})\lambda_{47}+(NV_{57}-L_{57})\lambda_{57}+(NV_{67}-L_{67})\lambda_{67}]CVV\leq \mathrm{r_{dis}} \tag{20}$$

$$\pi_{12}^0 = \left[1 + \sum_{n=1}^{s_1-1} C_n^{NV_{12}} \left(\frac{\lambda_{12}}{\mu_{12}}\right)^n + \sum_{n=s_1}^{NV_{12}} C_n^{NV_{12}} \left(\frac{n!}{s_1^{n-s_1} s_1!}\right) \left(\frac{\lambda_{12}}{\mu_{12}}\right)^n\right]^{-1} \tag{21}$$

$$\pi_{2j}^0 = \left[1 + \sum_{n=1}^{s_{2j}-1} C_n^{NV_{2j}} \left(\frac{\lambda_{2j}}{\mu_{2j}}\right)^n + \sum_{n=s_{2j}}^{NV_{2j}} C_n^{NV_{2j}} \left(\frac{n!}{s_{2j}^{n-s_{2j}} s_{2j}!}\right) \left(\frac{\lambda_{2j}}{\mu_{2j}}\right)^n\right]^{-1} \quad j = 3,7 \tag{22}$$

$$\pi_{4j}^0 = \left[1 + \sum_{n=1}^{s_{4j}-1} C_n^{NV_{4j}} \left(\frac{\lambda_{4j}}{\mu_{4j}}\right)^n + \sum_{n=s_{2j}}^{NV_{4j}} C_n^{NV_{4j}} \left(\frac{n!}{s_{4j}^{n-s_{4j}} s_{4j}!}\right) \left(\frac{\lambda_{4j}}{\mu_{4j}}\right)^n\right]^{-1} \quad j = 2,5,6,7 \tag{23}$$

$$\pi_{5j}^0 = \left[1 + \sum_{n=1}^{s_{5j}-1} C_n^{NV_{5j}} \left(\frac{\lambda_{5j}}{\mu_{5j}}\right)^n + \sum_{n=s_{5j}}^{NV_{5j}} C_n^{NV_{5j}} \left(\frac{n!}{s_{5j}^{n-s_{5j}} s_{5j}!}\right) \left(\frac{\lambda_{5j}}{\mu_{5j}}\right)^n\right]^{-1} \tag{24}$$

$$\pi_{6j}^0 = \left[1 + \sum_{n=1}^{s_{6j}-1} C_n^{NV_{6j}} \left(\frac{\lambda_{6j}}{\mu_{6j}}\right)^n + \sum_{n=s_{6j}}^{NV_{6j}} C_n^{NV_{6j}} \left(\frac{n!}{s_{6j}^{n-s_{6j}} s_{6j}!}\right) \left(\frac{\lambda_{6j}}{\mu_{6j}}\right)^n\right]^{-1} \tag{25}$$

$$\pi_{12}^n = \begin{cases} C_n^{NV_{12}} \left(\frac{\lambda_1}{\mu_1}\right)^n \pi_1^0 & 0 \le n \le s_1 \\ C_n^{NV_{12}} \left(\frac{n!}{s_1^{n-s_1} s_1!}\right) \left(\frac{\lambda_1}{\mu_1}\right)^n \pi_1^0 & s_1 \le n \le NV_{12} \end{cases} \tag{26}$$

$$\pi_{2j}^n = \begin{cases} C_n^{NV_{2j}} \left(\frac{\lambda_{2j}}{\mu_2}\right)^n \pi_{2j}^0 & 0 \le n \le s_{2j} \\ C_n^{NV_{2j}} \left(\frac{n!}{s_{2j}^{n-s_{2j}} s_{2j}!}\right) \left(\frac{\lambda_{2j}}{\mu_2}\right)^n \pi_{2j}^0 & s_{2j} \le n \le NV_{2j} \end{cases} \tag{27}$$

$$\pi_{4j}^n = \begin{cases} C_n^{NV_{4j}} \left(\frac{\lambda_{4j}}{\mu_4}\right)^n \pi_{4j}^0 & 0 \le n \le s_{4j} \\ C_n^{NV_{4j}} \left(\frac{n!}{s_{4j}^{n-s_{4j}} s_{4j}!}\right) \left(\frac{\lambda_{4j}}{\mu_4}\right)^n \pi_{4j}^0 & s_{4j} \le n \le NV_{4j} \end{cases} \quad j = 2,5,6,7 \tag{28}$$

$$\pi_{5j}^n = \begin{cases} C_n^{NV_{5j}} \left(\frac{\lambda_{5j}}{\mu_5}\right)^n \pi_{5j}^0; & 30 \le n \le s_{5j} \\ C_n^{NV_{5j}} \left(\frac{n!}{s_{5j}^{n-s_{5j}} s_{5j}!}\right) \left(\frac{\lambda_{5j}}{\mu_5}\right)^n \pi_{5j}^0 & s_{5j} \le n \le NV_{5j} \end{cases} \quad j = 3,7 \tag{29}$$

$$\pi_{6j}^n = \begin{cases} C_n^{NV_{6j}} \left(\frac{\lambda_{6j}}{\mu_6}\right)^n \pi_{6j}^0 & 0 \le n \le s_{6j} \\ C_n^{NV_{6j}} \left(\frac{n!}{s_{6j}^{n-s_{6j}} s_{6j}!}\right) \left(\frac{\lambda_{6j}}{\mu_6}\right)^n \pi_{6j}^0 & s_{6j} \le n \le NV_{6j} \end{cases} \quad j = 2,7 \tag{30}$$

$$L_{12} = \sum_{n=0}^{NV_{12}} n\pi_{12}^n \tag{31}$$

$$L_{2j} = \sum_{n=0}^{NV_{2j}} n\pi_{2j}^n \quad j = 3,7 \tag{32}$$

$$L_{4j} = \sum_{n=0}^{NV_{4j}} n\pi_{4j}^n \quad j = 2,5,6,7 \tag{33}$$

$$L_{5j} = \sum_{n=0}^{NV_{5j}} n\pi_{5j}^n \quad j = 3,7 \tag{34}$$

$$L_{6j} = \sum_{n=0}^{NV_{6j}} n\pi_{6j}^n \quad j = 2,7 \tag{35}$$

$$w_{12} = \frac{L_{12}}{(NV_{12} - L_{12})\lambda_{12}} \tag{36}$$

$$w_{2j} = \frac{L_{2j}}{(NV_{2j} - L_{2j})\lambda_{2j}} \quad j = 3,7 \tag{37}$$

$$w_{4j} = \frac{L_{4j}}{(NV_{4j} - L_{4j})\lambda_{4j}} \quad j = 2,5,6,7 \tag{38}$$

$$w_{5j} = \frac{L_{5j}}{(NV_{5j} - L_{5j})\lambda_{5j}} \quad j = 3,7 \tag{39}$$

$$w_{6j} = \frac{L_{6j}}{(NV_{6j} - L_{6j})\lambda_{6j}} \quad j = 2,7 \tag{40}$$

$$LQ_{12} = \sum_{n=1}^{NV_{12}} (n - s_{12})\pi_{12}^n \tag{41}$$

$$LQ_{2j} = \sum_{n=1}^{NV_{2j}} (n - s_{2j})\pi_{2j}^n \quad j = 3,7 \tag{42}$$

$$LQ_{4j} = \sum_{n=1}^{NV_{4j}} (n - s_{4j})\pi_{4j}^n \quad j = 2,5,6,7 \tag{43}$$

$$LQ_{5j} = \sum_{n=1}^{NV_{5j}} (n - s_{5j})\pi_{5j}^n \quad j = 3,7 \tag{44}$$

$$LQ_{6j} = \sum_{n=1}^{NV_{6j}} (n - s_{6j}) \pi_{6j}^{n} \qquad j = 2,7 \tag{45}$$

$$\lambda_{12} = \frac{1}{\frac{1}{T_{12}} + \frac{1}{T_{21}} + \frac{1}{\mu'_2}} \tag{46}$$

$$\lambda_{2j} = \frac{1}{\frac{1}{T_{2j}} + \frac{1}{T_{j2}} + \frac{1}{\mu'_j}} \quad j = 3,7 \tag{47}$$

$$\lambda_{4j} = \frac{1}{\frac{1}{T_{4j}} + \frac{1}{T_{j4}} + \frac{1}{\mu'_j}} \quad j = 2,5,6,7 \tag{48}$$

$$\lambda_{5j} = \frac{1}{\frac{1}{T_{5j}} + \frac{1}{T_{j5}} + \frac{1}{\mu'_j}} \qquad j = 3,7 \tag{49}$$

$$\lambda_{6j} = \frac{1}{\frac{1}{T_{6j}} + \frac{1}{T_{j6}} + \frac{1}{\mu'_j}} \qquad j = 2,7 \tag{50}$$

$$\mu'_i \geq 1 \tag{51}$$

$$\mu_{ij} \geq 1 \tag{52}$$

In equation (6) the model's objective function minimize amount of created environmental impact by transportation fleets through waiting and transportation time minimization, which also leads to energy reduction. Equation (7) illustrate that departure rate must be less than rate of transferring raw materials to supplier. Equation (8) emphasizes that entrance rate to manufacture from supplier, collection center and recycling center must be at least equivalent to total production rate. Equations (9) and (10) indicate that entrance rate from manufacture to disposal center and distribution center must be less than total production rate. Equation (11) indicates a constraint for providing demand. Equilibrium equations in the collection center are presented by (12)-(15). Equilibrium in repair center is indicated through equations (16) and (17) and in recycle center by (18) an (19). Equation (20) illustrate constraint of maximum capacity for disposal center. Equation (21) calculate the idle probability of server for loading in supplier and (22) similarly indicate this probability for manufacture which transfer products to distribution center and disposal center. Equation (23)–(25) illustrate idle probability of server for loading in collection center, repair center and recycle center respectively. Equations (26)–(30) consider probability of existing n server in supply chain's centers. Average number of customers in the system in different centers are calculated by equations (31)–(35). Average waiting time of each center is illustrated through (36)-(40) and average waiting time in queue is proposed in (41)-(45). Average time for a vehicle for returning to a center after departure from this center for going to other centers in loading system is calculated by equations (46)–(50). Equations (51) and (52) determine a lower bound for unloading and loading rate respectively.

3.4. Solution methods

Exact methods are used for solving the small size of mathematical models and generalized algebraic modelling system (GAMS) software is employed for achieving results of small size models. Besides, meta-heuristics methods are employed for solving large size optimization models with heuristics approaches. Genetic algorithm (GA) which is one of the meta-heuristics methods and belongs to the evolutionary algorithms (EA) class is employed for solving large size of our proposed bi-objective model. Genetic algorithm's capability in solving combinatorial multi-objective models made us use this approach for solving large size of our bi-objective model Rabbani et al. (2018). Finally, results of small and large size of problem are compared for validity investigation of genetic algorithm method.

4. Numerical example

4.1. Computational experiments

In order to evaluate model's performance, small and large size of problem is solved with exact and meta-heuristics approaches. GAMS software with BARON as its solver is used to solve the small size of the problem as well as employing genetic algorithm (GA) for the large size of the problem. Small size of the problem is solved with exact methods and the results of this approach will validate meta-heuristics method, which is used for solving the model in large size. Due to the long time, which is required for solving large size problem with GAMS software, meta-heuristics method is employed. First, a numerical example in small size is discussed and is solved with exact methods by GAMS software. Assumed value of parameters for small and large size of problem are indicated in Tables 1 and 2 respectively. We supposed a lower bound for loading and unloading rates and with this assumption model is solved. GAMS software's BARON solver is used for solving our NLP model. Meta-heuristics methods are used to find good solutions for an optimization problem with heuristic approaches when a large size problem is investigated. Genetic algorithm (GA) is employed for solving our model in large size. Large size of the problem is created by increasing the number of transportation fleets between centers and number of servers in centers besides increasing different rates of problem such as demand rate, rate of returning products and rate of transferring raw materials to supplier.

4.2. Model validation

In order to guarantee model' validity and reliability sensitivity analysis is performed on the number of transportation fleets to investigate its effect on the length of queue and waiting time. It is obvious that by increasing the number of transportation fleets

Table 1
Assumed value of model's parameters for small size of problem.

Parameters	value	Parameters	value	Parameters	value
$\boldsymbol{a}$	0.8	s_{45}	4	T_{23}	6.66
$\boldsymbol{P}_1$	0.15	s_{46}	3	T_{27}	2.85
$\boldsymbol{P}_2$	0.28	s_{47}	1	T_{42}	2.85
$\boldsymbol{P}_3$	0.47	s_{53}	2	T_{45}	2.22
$\boldsymbol{P}_4$	0.1	s_{57}	2	T_{46}	5
$\boldsymbol{r}_1$	0.8	s_{62}	4	T_{47}	2
$\boldsymbol{r}_2$	0.8	s_{67}	1	T_{53}	4
$\boldsymbol{cv}$	6	NV_{12}	10	T_{57}	2.5
$\boldsymbol{cvv}$	4	NV_{23}	8	T_{62}	6.66
$\boldsymbol{cvvv}$	12	..	2	T_{67}	4
$\boldsymbol{C}$	0.3	NV_{42}	4		
$\boldsymbol{r_d}$	155	NV_{45}	6		
$\boldsymbol{r_e}$	105	NV_{46}	4		
$\boldsymbol{r_{dis}}$	300	NV_{47}	2		
$\boldsymbol{r_s}$	250	NV_{53}	6		
$\boldsymbol{s}_{12}$	3	NV_{57}	3		
$\boldsymbol{s}_{23}$	4	NV_{62}	5		
$\boldsymbol{s}_{27}$	1	NV_{67}	2		
$\boldsymbol{s}_{42}$	2	T_{12}	6.66		

Table 2
Assumed value of model's parameters for large size of problem.

Parameters	value	Parameters	value	Parameters	value
a	0.8	s_{45}	10	T_{23}	6.66
P_1	0.15	s_{46}	9	T_{27}	2.85
P_2	0.28	s_{47}	3	T_{42}	2.85
P_3	0.47	s_{53}	5	T_{45}	2.22
P_4	0.1	s_{57}	8	T_{46}	5
r_1	0.8	s_{62}	8	T_{47}	2
r_2	0.8	s_{67}	5	T_{53}	4
cv	120	NV_{12}	16	T_{57}	2.5
cvv	50	NV_{23}	20	T_{62}	6.66
$cvvv$	350	NV_{27}	9	T_{67}	4
C	0.3	NV_{42}	13		
r_d	3000	NV_{45}	12		
r_e	2500	NV_{46}	12		
r_{dis}	400	NV_{47}	4		
r_s	2300	NV_{53}	9		
s_{12}	11	NV_{57}	9		
s_{23}	6	NV_{62}	11		
s_{27}	6	NV_{67}	7		
s_{42}	9	T_{12}	6.66		

length of queue in loading centers will increase and in queuing systems by increasing the number of customers more congestion will be existed in queue and length of the queue will increase. Fig. 3 indicate the sensitivity analysis for number of transportation fleets. It is indicated that by increasing the number of transportation fleets length of queue will increase (Fig. 3-a). Moreover, increasing the number of transportation fleets, will cause waiting time to increase (Fig. 3-b). As it is expected, Fig. 4 indicate that loading rate will increase by increasing the demand rate in distribution center. Since these findings comply with queuing systems, model is validated. Moreover a statistical model is presented in Appendix A for validating the proposed model and comparing the results of exact method and genetic algorithm approach.

5. Result and discussion

5.1. Result

The results of solving the model in small size with GAMS software are illustrated in Tables 3 and 4. Amount of objective function, which is gained from solving the model equals 65.451. Then, we solved our model by assuming lower and upper bound for loading and unloading rates. If we consider that loading rates must be less than 50 and unloading rates must be less than 20, objective function will increase to 65.559 and results will be as indicated in Tables 5 and 6.

The results of solving model with Genetic algorithm approach are indicated in Tables 7 and 8. Objective function for genetic algorithm approach is equivalent to 66.276. Since amount of obtained objective function with exact approach is equivalent to 65.559 and it does not have significant difference with amount of objective function in meta-heuristic approach, so genetic algorithm is operating properly. A statistical model in significance level of 0.005 is presented in Appendix A. This statistical model evaluate the hypothesis about the equality of objective function's value achieved by GAMS and by genetic algorithm approach. Regarding to 8 investigated samples by genetic algorithm, this evaluation indicates that there are not a significant difference between the results of

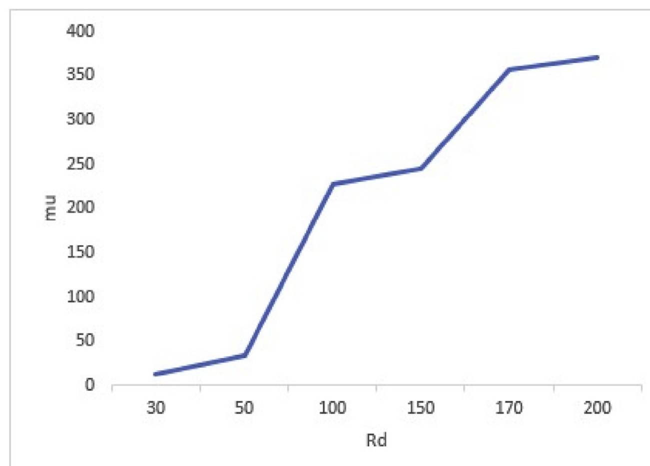


Fig. 4. Loading rate vs. rate of demand.

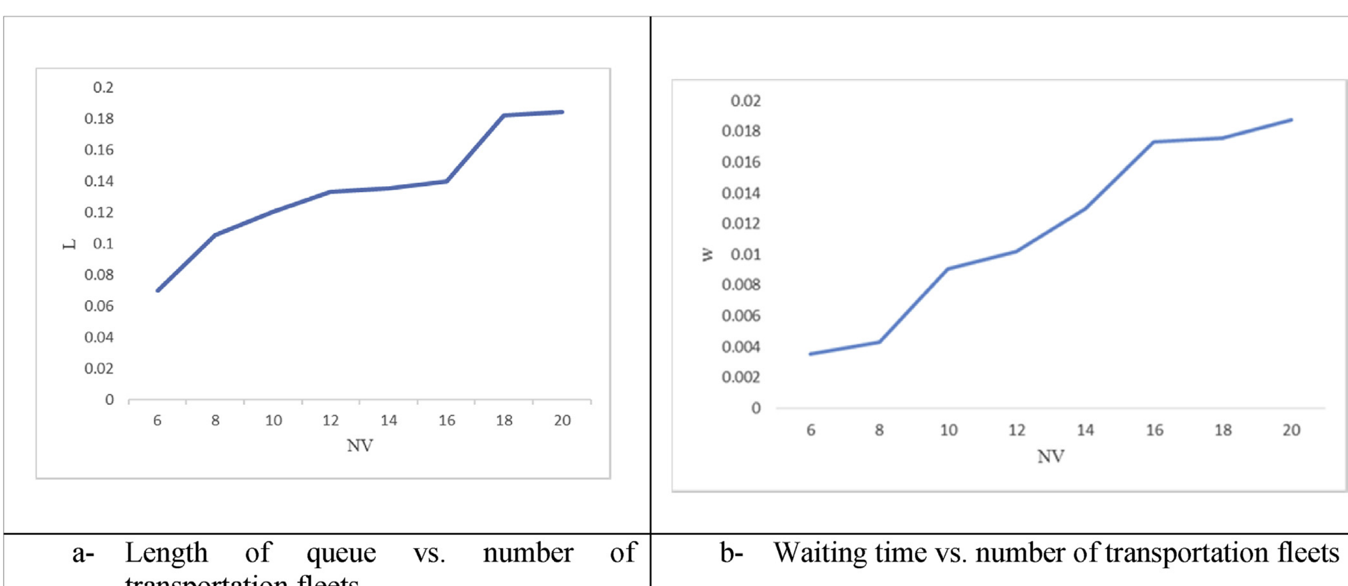


Fig. 3. Sensitivity analysis for number of transportation fleets.

Table 3
Model's results with lower bound consideration for loading and unloading rates for small size of problem.

Average number of transportation vehicles in centers		Average waiting time in queue for loading in centers		Average length of queue for loading in centers		total production rate	
L_{12}	0.029	w_{12}	0.003	LQ_{12}	$1.92{*}10^{-8}$	r_p	164.35
L_{23}	0.010	w_{23}	$1.47{*}10^{-4}$	LQ_{23}	0		
L_{27}	0.862	w_{27}	1.287	LQ_{27}	0.227		
L_{42}	1.657	w_{42}	0.898	LQ_{42}	0.277		
L_{45}	0.841	w_{45}	0.172	LQ_{45}	$3.77{*}10^{-4}$		
L_{46}	0.175	w_{46}	0.053	LQ_{46}	$4.84{*}10^{-4}$		
L_{47}	0.765	w_{53}	0.966	LQ_{53}	1.862		
L_{53}	3.787	w_{57}	1.064	LQ_{57}	0.067		
L_{57}	1.114	w_{62}	1.020	LQ_{62}	0.054		
L_{62}	2.698	w_{67}	1.326	LQ_{67}	0.263		
L_{67}	0.938						

Table 4
Model's results with lower bound consideration for loading and unloading rates for small size of problem.

Loading rate in centers		Unloading rate in centers		Idle probability of server for loading in centers		Average length of queue for loading in centers	
μ_{12}	399.9	μ'_2	1.752	π^0_{42}	0.142	λ_{42}	0.787
μ_{23}	2153.2	μ'_3	15.479	π^1_{42}	0.335	λ_{46}	0.864
μ_{27}	1.055	μ'_5	6.544	π^2_{42}	0.296	λ_{45}	0.95
μ_{42}	1.337	μ'_6	1.32	π^3_{42}	0.174	λ_{47}	0.5
μ_{45}	5.828	μ'_7	1	π^4_{42}	0.051	λ_{57}	0.556
μ_{46}	18.936			π^0_{12}	0.972	λ_{62}	1.148
μ_{53}	2.038			π^1_{12}	0.028	λ_{67}	0.667
μ_{57}	1			π^2_{12}	$3.65{*}10^{-4}$	λ_{12}	1.148
μ_{62}	1			π^3_{12}	$2.81{*}10^{-6}$	λ_{23}	2.74
μ_{67}	1			π^4_{12}	$1.9{*}10^{-8}$	λ_{53}	1.77

GAMS and genetic algorithm and null hypothesis is accepted. Convergence graph GA to optimal solution is indicated in Fig. 5.

Results of solving large size of the problem with Genetic algorithm approach is indicated in Tables 9 and 10. Convergence graph for solving the problem in large size is indicated in Fig. 6. Amount of objective function in this approach is equivalent to 724.857.

5.2. Sensitivity analysis

Analyzing model's sensitivity to parameters' changes leads to better understanding about model's behavior. Therefore, sensitivity analysis is performed for number of transportation fleets and it is indicated in Fig. 7. It is illustrated in Fig. 7 that objective function will have ascending behavior when number of transportation fleets increase. By increasing the number of transportation fleets, length of queue will increase in loading centers and therefore amount of created environmental impacts by vehicles will increase in network. Therefore, this increase in waiting time and amount of environmental impacts will lead to increase in objective function (Fig. 7-a). Besides, unloading rate in unloading centers will increase when number of transportation fleets increase. The ascending slope of this chart is not sharp because no queue will be formed in unloading centers, so unloading rate will not increase significantly. Meanwhile, increases the cost of unloading rate will cause more cost for the system (Fig. 7-b). Then sensitivity analysis is performed for capacity of transportation fleets. The relationship between medium capacity of transportation fleets and length of queue and waiting time is illustrated in Fig. 8. By increasing capacity of transportation fleets, more time is required for loading each of the transportation fleets. Therefore, service time for each customer

Table 5
Model's results with lower and upper bound consideration for loading and unloading rates for small size of problem.

Average number of transportation vehicles in centers		Average waiting time in queue for loading in centers		Average length of queue for loading in centers		total production rate	
L_{12}	0.229	w_{12}	0.02	LQ_{12}	$7.3{*}10^{-5}$	r_p	164.35
L_{23}	0.33	w_{23}	0.015	LQ_{23}	0.131		
L_{27}	0.862	w_{27}	1.287	LQ_{27}	0.227		
L_{42}	1.667	w_{42}	0.897	LQ_{42}	0.281		
L_{45}	0.511	w_{45}	0.104	LQ_{45}	$3.23{*}10^{-5}$		
L_{46}	0.346	w_{46}	0.104	LQ_{46}	$7.45{*}10^{-5}$		
L_{47}	0.8	w_{53}	0.981	LQ_{53}	1.913		
L_{53}	3.844	w_{57}	1.064	LQ_{57}	0.067		
L_{57}	1.114	w_{62}	1.021	LQ_{62}	0.056		
L_{62}	2.722	w_{67}	1.4	LQ_{67}	0.276		
L_{67}	0.966						

Table 6
Model's results with lower and upper bound consideration for loading and unloading rates for small size of problem.

Loading rate in centers		Unloading rate in centers		Idle probability of server for loading in centers		Average length of queue for loading in centers	
μ_{12}	50	μ'_2	1.803	π^0_{42}	0.14	λ_{42}	0.797
μ_{23}	1	μ'_3	20	π^1_{42}	0.333	λ_{46}	0.912
μ_{27}	1.055	μ'_5	4.543	π^2_{42}	0.297	λ_{45}	0.893
μ_{42}	1.342	μ'_6	1.435	π^3_{42}	0.177	λ_{47}	0.5
μ_{45}	9.582	μ'_7	1	π^4_{42}	0.052	λ_{57}	0.556
μ_{46}	9.637			π^0_{12}	0.793	λ_{62}	1.17
μ_{53}	2.03			π^1_{12}	0.186	λ_{67}	0.667
μ_{57}	1			π^2_{12}	0.02	λ_{12}	1.17
μ_{62}	1			π^3_{12}	0.001	λ_{23}	2.857
μ_{67}	1			π^4_{12}	$6.68*10^{-5}$	λ_{53}	1.818
				π^5_{12}	$3.13*10^{-6}$		
				π^6_{12}	$1.22*10^{-7}$		

Table 7
Model's results with Genetic algorithm approach for small size of problem.

Average number of transportation vehicles in centers		Average waiting time in queue for loading in centers		Average length of queue for loading in centers		total production rate	
L_{12}	0.386	w_{12}	0.012	LQ_{12}	$5.78*10^{-4}$	r_p	$1.0006*10^3$
L_{23}	0.230	w_{23}	0.009	LQ_{23}	$1.32*10^{-6}$		
L_{27}	0	w_{27}	0	LQ_{27}	0		
L_{42}	0.041	w_{42}	0.007	LQ_{42}	$6.7*10^{-6}$		
L_{45}	0.034	w_{45}	0.005	LQ_{45}	$4.53*10^{-11}$		
L_{46}	0.026	w_{46}	0.002	LQ_{46}	$2.41*10^{-9}$		
L_{47}	0	w_{53}	0.011	LQ_{53}	$3.25*10^{-4}$		
L_{53}	0.133	w_{57}	0.011	LQ_{57}	$4.11*10^{-6}$		
L_{57}	0.042	w_{62}	0.010	LQ_{62}	$4.14*10^{-8}$		
L_{62}	0.159	w_{67}	0	LQ_{67}	0		
L_{67}	0						

increase and this will lead to increase in length of queue and waiting time. Regarding the fact that objective function is consist of two main parts including transportation and waiting time, there will be less transportation fleets in routs when length of queue and waiting time increase and therefore first part of objective function will decrease. Since model is trying to minimize objective function, optimum solution is one, which minimize summation of transportation time and waiting time. To achieve optimality besides increasing capacity, increasing the length of queue will continue until the summation and the amount of demand are minimized. By increasing fleets' capacity, more products will be transferred and after a point, this increase in transportation will cause reduction in number of transportations and therefore length of queue. Therefore, when capacity increase first length of queue increase and then after transferring more products than before, number of transportations for supplying demand will decrease and this will lead to reduction in length of queue and waiting time (Fig. 8-a, Fig. 8-b). The relationship between capacity of transportation fleets and objective function is also indicated in Fig. 8. First, by increasing the capacity of vehicles, the first part of objective function which indicates transportation time between centers decreases and this reduction in objective function is dependent on transportation cost per unit of distance which can lead to the reduction of objective function when increases. On the other hand, most of the vehicles are available in loading centers and this increase in capacity cause extra congestion. Therefore, waiting time for transportation fleets

Table 8
Model's results with Genetic algorithm approach for small size of problem.

Loading rate in centers		Unloading rate in centers		Idle probability of server for loading in centers		Average length of queue for loading in centers	
μ_{12}	81.601	μ'_1	799.554	π^0_{12}	0.674	λ_{12}	3.277
μ_{23}	11.327	μ'_2	194.461	π^0_{23}	0.791	λ_{23}	3.300
μ_{27}	47.030	μ'_3	333.369	π^0_{27}	1	λ_{27}	0
μ_{42}	135.237	μ'_4	681.071	π^0_{42}	0.959	λ_{42}	1.418
μ_{45}	193.207	μ'_5	777.737	π^0_{45}	0.966	λ_{45}	1.109
μ_{46}	378.603	μ'_6	472.586	π^0_{46}	0.974	λ_{46}	2.486
μ_{47}	391.809	μ'_7	179.607	π^0_{47}	1	λ_{47}	0
μ_{53}	87.861			π^0_{53}	0.874	λ_{53}	1.988
μ_{57}	87.444			π^0_{57}	0.958	λ_{57}	1.241
μ_{62}	99.365			π^0_{62}	0.850	λ_{62}	3.277
μ_{67}	234.508			π^0_{67}	1	λ_{67}	0

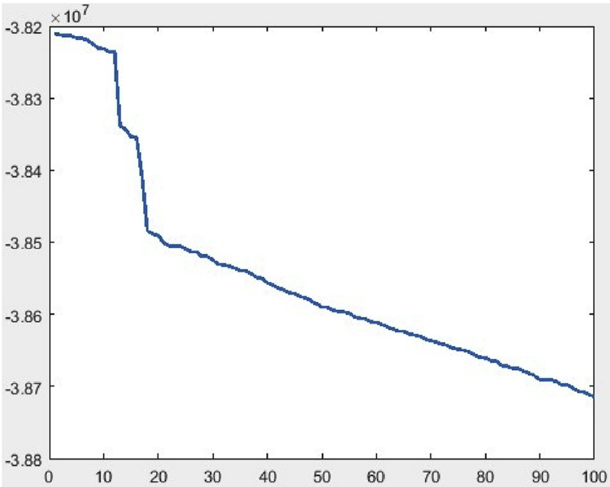


Fig. 5. Convergence of GA to optimal solution.

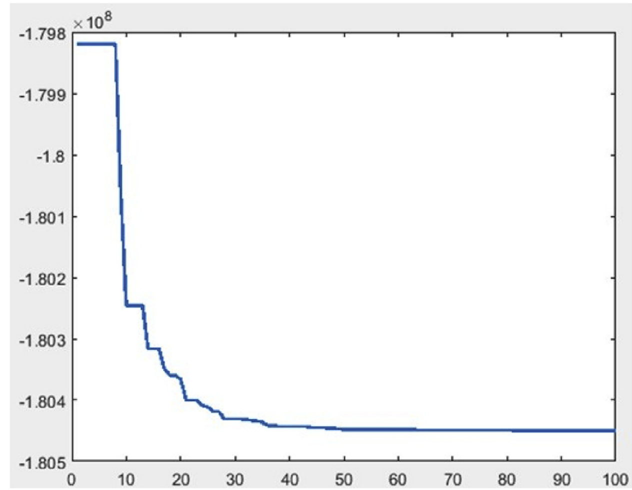


Fig. 6. Convergence of GA to optimal solution for large size of problem.

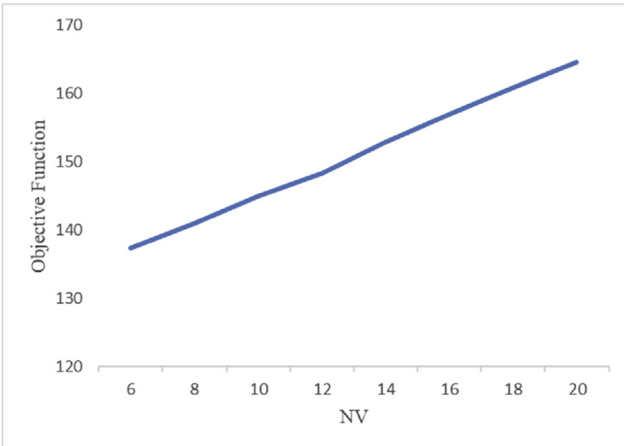
Table 9
Model's results with Genetic algorithm approach for large size of problem.

Average number of transportation vehicles in centers		Average waiting time in queue for loading in centers		Average length of queue for loading in centers		total production rate	
L_{12}	3.965	w_{12}	0.012	LQ_{12}	$1.804*10^{-19}$	r_p	20.578
L_{23}	0.838	w_{23}	0.003	LQ_{23}	$4.927*10^{-59}$		
L_{27}	0.129	w_{27}	0.004	LQ_{27}	$1.475*10^{-19}$		
L_{42}	0.310	w_{42}	0.005	LQ_{42}	$5.713*10^{-34}$		
L_{45}	0.198	w_{45}	0.003	LQ_{45}	$3.775*10^{-87}$		
L_{46}	0.451	w_{46}	0.004	LQ_{46}	1.096*10-52		
L_{47}	0.055	w_{47}	0.002	LQ_{47}	$1.440*10^{-23}$		
L_{53}	0.753	w_{53}	0.006	LQ_{53}	$6.469*10^{-25}$		
L_{57}	0.180	w_{57}	0.004	LQ_{57}	$3.503*10^{-40}$		
L_{62}	0.596	w_{62}	0.003	LQ_{62}	$3.126*10^{-70}$		
L_{67}	0.136	w_{67}	0.003	LQ_{67}	$2.571*10^{-19}$		

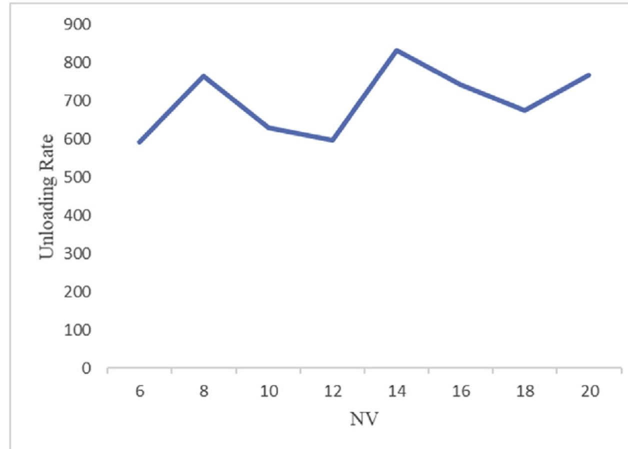
Table 10
Model's results with Genetic algorithm approach for large size of problem.

Loading rate in centers		Unloading rate in centers		Idle probability of server for loading in centers		Average length of queue for loading in centers	
μ_{12}	80.072	μ'_1	570.873	π^0_{12}	0.017	λ_{12}	3.306
μ_{23}	313.378	μ'_2	405.378	π^0_{23}	0.430	λ_{23}	3.318
μ_{27}	218.720	μ'_3	730.148	π^0_{27}	0.878	λ_{27}	1.425
μ_{42}	182.263	μ'_4	488.423	π^0_{42}	0.732	λ_{42}	1.423
μ_{45}	334.660	μ'_5	736.774	π^0_{45}	0.819	λ_{45}	1.109
μ_{46}	218.277	μ'_6	765.915	π^0_{46}	0.635	λ_{46}	2.491
μ_{47}	356.892	μ'_7	586.314	π^0_{47}	0.945	λ_{47}	0.998
μ_{53}	265.765			π^0_{53}	0.468	λ_{53}	1.994
μ_{57}	205.554			π^0_{57}	0.834	λ_{57}	1.247
μ_{62}	274.014			π^0_{62}	0.549	λ_{62}	3.306
μ_{67}	290.673			π^0_{67}	0.872	λ_{67}	1.993

in loading centers increases, which cause more increase in the second part of objective function than reduction in the first part of it and consequently the total objective function, will increase. Therefore, optimum capacity is where transportation and waiting time are in balance and they minimize the objective function (Fig. 8-c). Fig. 9 indicate the behavior of loading rate vs. number of servers. First with increasing the number of servers, loading rate will decrease because more servers are available for loading and high loading rate is not required. This increase in number of transportation fleets make vehicles spend less time in loading centers and then they enter the routes between center. In fact, when transportation fleets spend less time in loading centers, number of transportation fleets between centers will increase which leads to increase in entrance rate of customers to loading centers and consequently loading rate in loading center will increase. As it is shown in Fig. 10 by increasing the rate of returning products first objective function decreases because requirement to transportation of raw materials from supplier decreases and a part of rout which is transferring raw materials from supplier for providing demand will be omitted. Moreover, since a part of

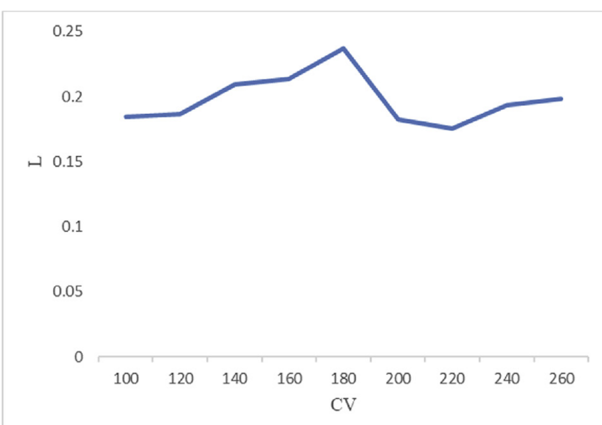


a- Objective function vs. number of transportation fleets

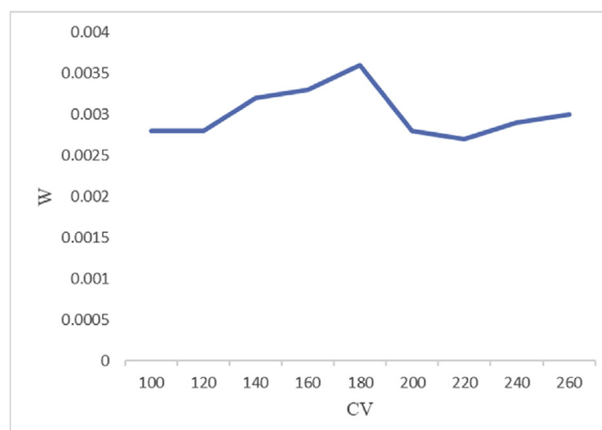


b- Unloading rate vs. number of transportation fleets

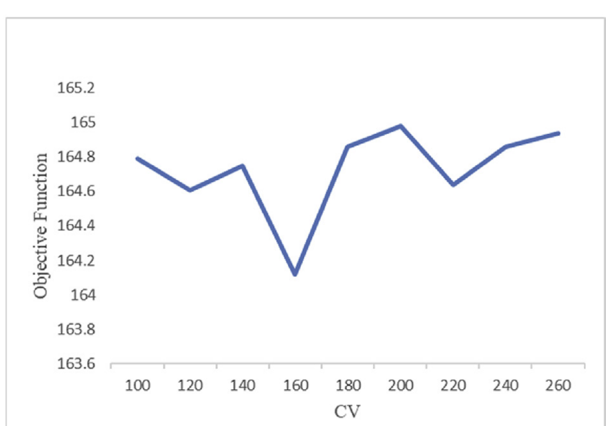
Fig. 7. Sensitivity analysis for number of transportation fleets.



a- Length of queue vs. capacity of transportation fleets



b- Waiting time vs. capacity of transportation fleets



c- Objective function vs. capacity of transportation fleets

Fig. 8. Sensitivity analysis for capacity of transportation fleets.

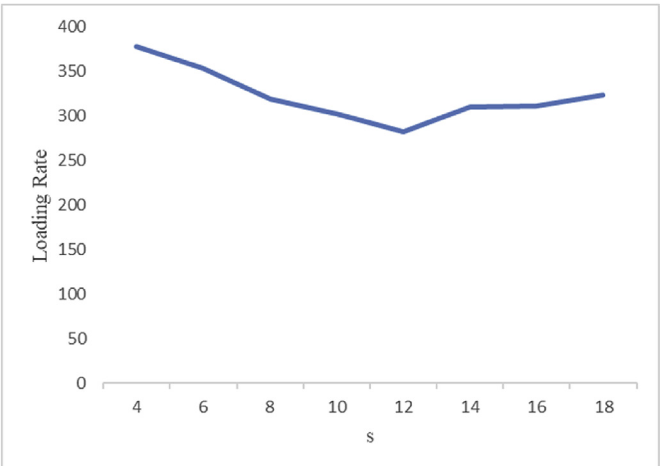


Fig. 9. Loading rate vs. number of servers.

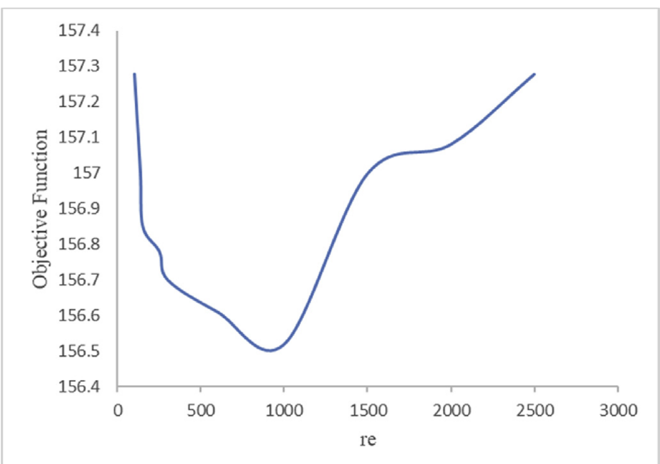


Fig. 10. Objective function vs. rate of returned products.

returned products after repair is transferred to distribution center, the need to produce products will decrease. Then, because of the extra return of products, more transportation will be required between collection centers and the recycle center, repair center, production system and waste center and this increase is more than what is provided in saving by recycling which causes increase in objective function.

5.3. Discussion

This research has some practical aspects and marginal impacts. Considerable amounts of researches such as Fazli-Khalaf et al. (2017) and Yu and Solvang (2018) have concentrated on green supply chain without considering all possible conditions, which can exist for products. In fact, in this research for approaching the presented model to real world conditions different situations for products such as being repairable, recyclable, reusable or being waste is investigated. In this way, all environmental impacts for the supply chain are considered in the model. Moreover, parts of the literature, which is related to green supply chain like (Ghomi-Avili et al., 2018), investigated the environmental impacts only in supply chains' centers while transportation fleets, which are studied in our research, create considerable amounts of environmental impacts. In fact, our article has similar point of view toward the problem of green supply chain design as Aziziankohan et al. (2017) with the aim of reducing waiting and transportation time for environmental impacts reduction. Aziziankohan et al. (2017) did not considered all of the mentioned conditions in the supply chain. Moreover, in this article green closed loop supply chain is studied by a new point of view, which differentiates this work from previous ones. This distinction is achieved by considering transportation fleets in each parts of supply chain as customers of a finite source queuing system in loading centers which approaches the presented model to real world circumstances and is another marginal implication of model. Therefore, based on queuing systems with finite source description in (Ross, 2014; Kleinrock, 1975; Bunday and Scraton, 1980), loading system in each part of supply chain is considered as a G/M/S queuing system with finite source. Another advantage of this research is that by specifying loading rate in different centers, waiting time of transportation fleets in loading queue will be minimized. Moreover, by determining unloading rate, total transportation and waiting time will be minimized and environmental impacts will be reduced by this approach. Therefore, decision makers can specify the optimum amount of human resource allocation and different machines in loading and unloading systems. Aziziankohan et al. (2017) assumed the number of transportation fleets as variable but in many cases, supply chain has a specific number of transportation fleets and based on them and by specifying the rate of servicing in loading and unloading servers, environmental impacts are minimized.

6. Conclusion and future research

In this paper, a bi-objective NLP model for green supply chain network with reverse logistics consideration is discussed. In order to approach this problem to real world conditions, four levels for forward flow and four levels for reverse flow are considered. For the first time, transportation fleets are assumed as customers of a G/M/S queuing system with finite source in each part of the supply chain. This contribution will help achieving model's objective, which is optimization of energy consumption and reducing created environmental impact by transportation fleets through transportation and waiting time reduction in loading centers. Assuming forming queue in loading centers and providing service in centers is another assumption in the article. All of the conditions for a reversed product from customer such as recycle, repair, remanufacture and considering as waste are also investigated in this article. These contributions will make the presented model closer to real world circumstances and will make this article different from previous researches. The practical contributions of paper are: (1) Presenting a comprehensive model through considering queuing system for a green supply chain with reverse logistics consideration in order to decrease energy consumption and environmental impacts creation. (2) Green supply chain monitoring is discussed through congestion consideration of transportation fleets, which affect environmental impacts. Theoretical contributions of paper consist of: (3) Employing a G/M/S queuing system with finite source for loading systems of a green supply chain with reverse logistics consideration. (4) Assuming transportation fleets as customers of a queuing system in loading systems and considering no queue in unloading systems due to sufficient number of servers. (5) Reaching a comprehensive model by assuming S servers for each loading systems. To indicate model's applicability, a numerical example is presented. Presented model is solved with exact method in small size with GAMS software and then genetic algorithm as a meta-heuristics approach is employed for solving the large size of problem. After solving the proposed model with exact method, effects of important parameters on model's function is investigated through performing a sensitivity analysis. Behavior of objective function vs. rate of returned products and number of transportation fleets is investigated. Effects of number of transportation fleets and capacity of them are studied on length of queue. Loading and unloading behavior and waiting time behavior is investigated vs. model's parameters. It is concluded that increasing the number of transportation fleets will cause more environmental impact and energy consumption while increasing the capacity of transportation fleets first will cause reduction in objective function and after a point will increase the amount of environmental impact and energy consumption. On the other hand, increase in the rate of returned products first decreases the amount of objective function and after a point, extra return of products will cause increase in amount of environmental impact and energy consumption. For future researches, consideration of queuing system in unloading system can also be studied. Discussing the number of transportation fleets and rate of servicing to customers as model's variables is another approach in future researches.

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Appendix A

In this section the hypothesis about the equality of objective function's value achieved by GAMS and by genetic algorithm approach is evaluated. Therefore, a sample with the size of 8 is considered from objective function and is achieved by solving the genetic algorithm 8 times. Then the normal probability plot for these data is plotted in Minitab software. Kolmogorov-Smirnov test is used for evaluating the normality and its result is indicated in Fig. 15. As it is obvious in this figure and regarding to p-value which is more than 0.05, assuming normal distribution for these data is rational. Therefore, according to (Montgomery, 2017) we can use the following hypothesis test when population variance is not specified.

$$\begin{cases} H_0: Z_{GA} = 65.559 \\ H_1: Z_{GA} > 65.559 \end{cases} \quad (53)$$

The statistic for this test is calculated by equation (54):

$$t_0 = \frac{\overline{Z_{GA}} - 65.559}{S/\sqrt{8}} \quad (54)$$

Besides S is calculated by equation (55):

$$S = \sqrt{\frac{\sum_{i=1}^{100} \left(Z_{GAi} - \overline{Z_{GA}}\right)^2}{7}} \quad (55)$$

and its acceptance region is $(-\infty \;\; t_{\alpha,7}]$.

Based on the investigated sample, values of S and $\overline{Z_{GA}}$ are 0.6024 and 66.28 respectively. Therefore t_0 is calculated as follows:

$$t_0 = \frac{\overline{Z_{GA}} - 65.559}{S/\sqrt{8}} = \frac{66.28 - 65.559}{0.6024/2.828} = 3.384$$

In the significance level of 0.005, acceptance region will be $(-\infty \;\; 3.499]$. The statistic of the test is in the acceptance region and null hypothesis is accepted in significance level of 0.005. Therefore, there are not a significant difference between the results of GAMS and genetic algorithm.

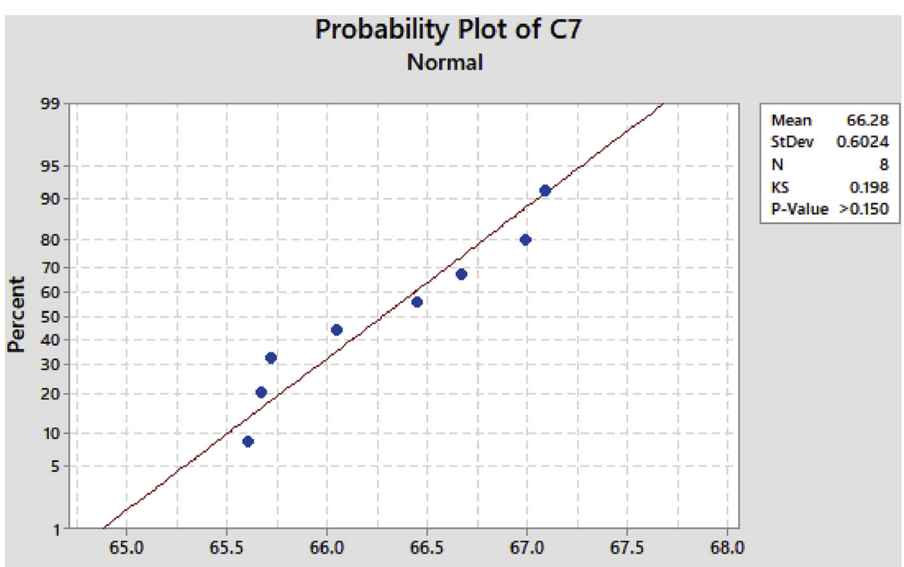

Fig. 15. The result of Kolmogorov-Smirnov test to evaluate the normality assumption

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