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Abstract: The increasing demand for rail transport necessitates an effective transportation network design for the shipment of goods with minimum cost and time. Since the breakdown of wagons is a main delay factor in rail transportation, the maintenance and repairs of defective wagons becomes prominent. In this study, main stations are considered as hubs, and hubs are places where defective wagons are collected. For this purpose, a robust multi-objective mathematical model is proposed to minimise transportation costs considering customer demand. Also, the model seeks to minimise the total transportation time and emissions. The AEC method is exploited to solve and validate the proposed model. Moreover, the sensitivity analysis is performed to demonstrate the effect of changing the main parameters on the outcomes. The results show that repairs and maintenance can affect the capacity. Also, the findings demonstrate the applicability and validity of the proposed model in the railway sector. [Submitted: 29 May 2023; Accepted: 16 January 2024]

Keywords: railway transportation; sustainability; hub location-allocation; maintenance; repair; augmented epsilon constraint; AEC.

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1 Introduction

The transportation sector is one of the fundamental elements of the world’s economy and has a great impact on economic growth. This sector connects different economic sectors with each other and links the markets in the movement of goods and services (Farahani et al., 2013; Zhalechian et al., 2017). In addition, the transportation sector plays a crucial role by facilitating the movement of passengers (Zhang et al., 2021).

Despite the advantages of rail transportation such as the possibility of transporting high-tonnage cargo over long distances, saving fuel, reducing environmental pollution, and increasing security, many cargo owners are not willing to use railways (Wagner, 2008). Transportation time can be stated as one of the main obstacles to attracting cargo owners in choosing railroads. Due to disruptions in lines, fleets, and locomotives as well as unplanned cargo trains, there is a possibility of delays and the subsequent late arrival of cargo in the rail transportation network compared to the road transport (Zanjirani et al., 2013). The occurrence of delays depends on various factors such as the interference of cargo trains with passenger trains, line failure, signal failure, accident, delay in loading and unloading, diesel failure, wagon failure, etc. (Heidari et al., 2021). These delays prevent owners from using rail transportation and choosing road transportation as the best option. Despite some solutions have been proposed to reduce delays in the railways, the breakdown of wagons as one of the substantial causes of delays has been neglected so far. Hence, in this research, the breakdown of wagons has been addressed as one of the main causes of delay (Kayışoğlu and Akgün, 2021). Improving the wagon maintenance can significantly reduce breakdowns, derailments, and delays, which can increase network productivity, capacity, and reliability (Schlake et al., 2011; Nagy and Csiszár, 2015).

In addition to the late arrival of the cargo to the destination, the breakdown of the wagons hinders the optimal operation of the stations. In such a way that any disturbance in the station can occupy at least one of the lines of the station and disrupt the normal cycle of the fleet (Limbourg and Jourquin, 2009). Carrying out repairs in defective freight wagons is another cause of delays that imposes various costs. The most important effect of wagon repair on the rail network is the disruptions of the train's schedule (the train to which the wagon is connected) and also the passenger and freight trains that are passing through (Jeong et al., 2007). Therefore, focusing on the repairs of defective cargo wagons prevents many problems, increases the speed of travel, optimises the usage of the wagons' capacity, and eventually increases the satisfaction of the cargo owners, their desire to use railroads, and the share of rail transportation.

In the past, repair operations aimed to optimise the availability of equipment with minimum cost, while nowadays social and environmental aspects have been addressed in addition to the economic aspect (Heidari et al., 2021). Also, the goods were directly transferred from the origins (suppliers) to the demand destinations in traditional service networks (Soleimani et al., 2021). However, in modern networks, a number of intermediate points in the network are selected so that the flow of demand is transferred from the origin to the destination through these intermediate points which are called hubs. These hubs (stations) are exploited for transferring goods and providing value-added services at a reasonable cost for freight owners and users of the rail network (O'Kelly, 1987; Topcuoglu et al., 2005; Ernst and Krishnamoorthy, 1996; Liu et al., 2012; De Camargo et al., 2008; Correia et al., 2017; Zhalechian et al., 2017). Hub location plays a fundamental role in network design because the total cost of transportation affects the capacity of intermediate centres and therefore the service time and the amount of congestion in the system. Any problem that may occur in a station will increase cost, delivery time, dissatisfaction of the cargo owners, and eventually decrease the share of rail transportation. The studies conducted in the rail network reveal that many solutions such as train scheduling and hub usage have been proposed to reduce the delays. However, the disturbance in the wagons entering the station has not been investigated as a cause of delay in railroads.

In the present research, one of the causes of delay that occurs through the breakdown of the freight wagons is addressed. Also, different types of repairs as well as the usage of hubs are considered in the proposed optimisation model in order to reduce the cost, time, and pollution in addition to optimising the operation of railway stations. In other words, in this study, the problem of managing the maintenance and repairs of defective wagons is investigated as the railway hub logistics network design. The use of railway hub stations can lead to a reduction in service delivery time in addition to significantly reducing cost. In fact, the order integration channels and transportation management through highways created between hubs reduce the operational costs of transportation and the emissions of the pollutant. In addition, real-world conditions such as the time discount coefficient in inter-hub transportation are taken into account as there are various examples where cargo consolidation and transportation management can reduce operational costs.

The main contributions of the current research can be stated as follows:

- Using hubs in the rail network for defective wagons.
- Defining the environmental and social functions for the collection of defective wagons.
- Reducing the delays in the arrival of freight wagons.
- Providing a sustainable multi-objective mathematical programming model for the collection and repair of defective wagons in the rail transport network.

The remaining of this paper is structured as follows: a review of the relevant studies is provided in Section 2. In Section 3, the problem is defined and the proposed optimisation model is presented. Solution approach is explained in Section 4. Computational results are given in Section 5. Finally, Section 6 concludes the paper.

2 Literature review

Several researchers have studied various hub location problems so far. This attention reveals the necessity of creating new infrastructures for transportation and communication systems as these systems no longer follow traditional network models due to design of complex systems. Since 1985, many articles have been presented in the field of hubs and their applications in various industries. Verma et al. (2017) investigated the hub and spoke network of the urban bus services in order to find the optimal hub locations, assign non-hub nodes to hub nodes, and create inter-hub and intra-hub routes. In addition, Sender et al. (2017) addressed a capacitated hub location-allocation problem and solved it using two metaheuristic algorithms. Also, Sarker et al. (2018) developed an optimisation model considering minimal cost for the logistics design system of bio-methane gas production. Moreover, Bashiri et al. (2018) addressed a p-hub location problem in a dynamic environment considering mobile facilities inside the hub nodes.

Mostert et al. (2018) proposed a bi-objective model for minimising costs and environmental effects of the freight transpiration network. Besides, Wang et al. (2018) suggested a bi-objective mathematical programming model for designing the hub-and-spoke-based intermodal railroad transportation network. Also, Fotuhi and Huynh (2018) studied the expanding problem of intermodal freight network considering multiple periods. In addition, Fazayeli et al. (2018) proposed a multi-objective mathematical programming model for the location-routing multimodal transportation network problem. Later on, Kahag et al. (2019) proposed a bi-objective mathematical model incorporating the minimisation of cost and time for the intermodal hub-location-allocation problem in which both the origin and the destination hub facilities were taken into account as an *M*/*M*/*m* queuing system. Also, Khodemani-Yazdi et al. (2019) studied a bi-objective hierarchical hub location problem considering hub facilities as service centres and sought to minimise the total costs and maximal route length. In addition, Maiyar and Thakkar (2019) presented a sustainable intermodal food grain transportation model considering hub disruption.

Abbassi et al. (2019) presented a robust optimisation model considering uncertainty in cost and terminal capacity for the intermodal freight transportation problem. Moreover, Dukkanci et al. (2019) addressed the green hub location problem in which the best locations for hubs were determined and the demand nodes were allocated to the hubs with the aim of minimising the total amount of emissions. Subsequently, Hu et al. (2020) proposed a bi-objective mathematical model incorporating the cost minimisation and the maximisation of system utilisation. Also, Basirati et al. (2020) suggested a bi-objective mathematical model for minimising the total costs including the fixed costs associated with hub location, allocating, handling, and travelling costs. Then, this problem was solved using an AEC method for small to medium-sized numerical problems. In addition, Xu et al. (2020) proposed a fuzzy bi-objective optimisation model for minimising the transportation cost and time of the hub-and-spoke rail-road network.

Mokhtarzadeh et al. (2021) presented a multi-objective mathematical model considering the objective functions of minimising noise pollution, cost, and the harassment brought by the hub construction. In addition, Zhao et al. (2021) developed an optimisation model considering the hub-and-spoke structure for establishing an intra-city subway logistics network. In addition, Shang et al. (2021a) presented a bi-objective model for the hierarchical multimodal hub location problem in order to minimise the total costs and delivery time. Also, Zahiri and Suresh (2021) addressed the hub location problem for the transportation network of hazardous materials under uncertainty. Moreover, Kim and Kim (2021) identified the optimal locations of infrastructure maintenance depots for keeping particular vehicles and efficiently and timely supporting the maintenance and inspection operations. Furthermore, Yu and Jiang (2021) developed a bi-level optimisation model for the parcel delivery problem in the integrated air-rail transportation network. In addition, Shang et al. (2021b) investigated the hierarchical multimodal hub location problem for cargo delivery system and proposed a fuzzy programming model based on credibility considering the uncertainty of the transportation time as well as the handling time associated with the cargo delivery system.

Kurtuluş and Ercan (2022) developed a multi-objective optimisation model including minimising total costs and emissions for the location-allocation problem considering volume discounts and empty container relocation. Also, Zhang et al. (2022) studied many-to-many distribution and transportation systems and proposed a stochastic incomplete multimodal hub location model considering delivery-time and multiple assignments. In addition, Hu et al. (2022) developed a bi-objective dynamic model for the location-allocation-routing problem of the underground logistics system network to minimise construction and operating costs. Moreover, Zhou et al. (2022) considered differentiated services and several transportation modes in the hub-and-spoke railway network permitting customers to select the favourable service levels. Furthermore, Farazmand et al. (2022) developed a bi-objective optimisation model to minimise the total costs and environmental effects in the multimodal logistics network. Also, Mohri and Thompson (2022) designed a sustainable intermodal freight transportation network applying a controlled rail tariff discounting short-term policy. In addition, Anoop and Vinay (2022) developed a single period and a multi-period optimisation model considering volume discount on rail freight rate for the multimodal freight transportation problem. Moreover, Salimifard and Bigharaz (2022) reviewed the literature of the multi-commodity network flow between 2000 and 2019. Furthermore, Alp Ertem et al. (2022) suggested a mathematical programming model for the problem of shipping relief supplies in the capacitated multi-period multi-commodity intermodal transportation network. Also, Khaleghi and Eydi (2022) developed an optimisation model taking the linear time-dependent demand into account for a multi-period hub network design in an ongoing time planning horizon.

Table 1 A brief review of relevant studies

Author	*Objective function*			*Collecting defective wagons for repair*	*Locating*	*Allocating*	*Delay*	*Solution method*
	Economic	*Environmental*	*Social*					
Verma et al. (2017)	*				*	*		GA
Zhalechian et al. (2017)	*	*	*		*	*		NSGAII
Mostert et al. (2018)	*	*			*			EC-NSGAII
Kahag et al. (2019)	*		*			*		EC
Xu et al. (2020)	*				*			GA
Shang et al. (2021a)	*		*			*		EC-NSGAII
Heidari et al. (2021)	*	*	*		*			EC-NSGAII
Shang et al. (2021b)	*					*		CPLEX
Kurtuluş and Ercan (2022)	*	*			*	*		EC
Pardis and Farimani (2023)	*				*	*		PSO
Khaleghi and Eydi (2023)	*		*				*	EC
This study	*	*	*	*	*	*	*	AEC

Zavareh et al. (2022) proposed the optimal preventive maintenance scheduling for the emergency rescue wagons in railway networks employing a genetic algorithm.

Subsequently, Pardis and Farimani (2023) investigated the hub location-allocation problem and supposed a bi-objective model taking the minimisation of handling time, cost, and delay triggered by congestion in the hubs into account. In addition, Ziar et al. (2023) presented a bi-level p-hub median model for the location problem of dry ports considering direct transportation between nodes in the rail roads. Also, Khaleghi and Eydi (2023) proposed a sustainable multi-objective mathematical programming model for a multi-period hub location problem considering demand changes.

A review of the literature demonstrates that no study has considered hubs in the rail network for defective wagons. Also, there exists no research addressing the environmental and social functions for the collection of defective wagons. In addition, no optimisation model has been proposed for reducing the delays in the arrival of freight wagons so far. Moreover, there is no study in which a sustainable multi-objective optimisation model was developed for the collection and repair of defective wagons in the rail transport network. Table 1 presents a brief review of literature survey.

3 Problem definition and mathematical programming model

In this study, a mathematical programming model is proposed for the problem of managing the repairs of wagons with the aim of reducing the delay in receiving customer requests. According to the available statistics, the wagon breakdown is an important reason for the delay in receiving customers' requests. It is clear that doing any repair requires spending time and money and causes delays. One of the fundamental solutions for this problem is to create appropriate communication channels to collect broken wagons and send them to the nearest repair centre. It is also necessary to unload the wagons and their cargo is delivered to the customers by other trains. It should be noted that if the defective wagons are not removed from the train, the train must be stopped until the repairs are completed, which causes a lot of delays. Improving the wagon maintenance can significantly reduce breakdowns, derailments, and delays, which can increase network productivity, capacity, and reliability (Schlake et al., 2011; Nagy and Csiszár, 2015).

Therefore, in this research, an optimisation model is presented for minimising the transportation costs according to the demand level of each customer (station). It is assumed that some stations, which have more suitable technical and communication infrastructures, are selected as hubs, and defective wagons are sent to other stations through communication networks between hubs, as a result, both cost and delivery time will be reduced.

3.1 Indices

N $\{i, j\}$ set of stations.

H $\{k, l\}$ set of potential stations for establishing hub.

3.2 Parameters

FH_k The fixed cost of creating the necessary infrastructure in the potential station k as a hub ($).

f_{ij}	Flow of wagons between two stations (ton).
$\hat{C}_{ij}$	Cost of direct transportation between two stations (\$).
C_{ij}	Cost of usual transportation between two stations (\$).
HL_{kl}	Inter-hub network connection cost (\$).
cap	Capacity of trains for carrying defective wagons (ton).
CV	Cost of using a locomotive for transporting wagons (\$).
d_{kl}	Cost of unloading and loading wagons between hubs k and l (\$).
EV_{ij}	The amount of biological pollution caused by transportation between two stations (kg-CO_2/km).
ES_{ij}	The amount of noise pollution caused by transportation between two stations (db).
tt_{ij}	Transportation time between two stations (min).
ot_k	Required operating time in hub k (min).
α	Inter-hub time discount coefficient (min).
SB_{ij}	Time range for sending equipment between two stations (min).
ICG_{kl}	The cost of transporting goods between hubs k and l (\$).
M	A large number.

It should be noted that $\hat{C}_{ij}$ denotes direct transportation cost, which means that if we travel directly from i to j, the associated transportation cost is $\hat{C}_{ij}$. Also, C_{ik} denotes usual transportation cost, which means that if we move from i to j through a hub, the associated transportation cost is C_{ik}.

3.3 Decision variables

H_k	If a station at potential location k is selected as a hub, one; otherwise, zero.
$\hat{Y}_{ij}$	If direct transportation between two stations exists, one; otherwise, zero.
Y_{ijkl}	If transportation between two stations takes place through the hubs k and l, one; otherwise, zero.
Z_{kl}	If two hubs k and l are linked, one; otherwise, zero.
X_{ik}	If station i is assigned to hub k, one; otherwise, zero.
num_{kl}	The number of locomotives required between hubs k and l.
TFM_{kl}	The number of wagons transported between hubs k and l.
ST_{ij}	Transportation time of wagons between two stations.

3.4 Mathematical programming model

$$Min \sum_{k} FH_k H_k + \sum_{k,l:k\neq l} HL_{kl} Z_{kl} + \sum_{i,j} f_{ij} \hat{C}_{ij} \hat{Y}_{ij} + \sum_{i,j:i\neq i,k,l:k\neq l} \left(C_{ik} + C_{kj}\right) Y_{ijkl} f_{ij} + \sum_{k,l:k\neq l\neq} ICG_{kl} + \sum_{k,l:k\neq l} \left(\left(\sum_{i,j:i\neq j} f_{ij} Y_{ijkl} \right) (C_{kl} + d_{kl}) \right) \tag{1a}$$

$$Min \sum_{i,j:i\neq i,k,l:k\neq l} \left(EV_{ik} + EV_{kj}\right) Y_{ijkl} f_{ij} + \sum_{i,j:i\neq i,k,l:k\neq l} \left(ES_{ik} + ES_{kj}\right) Y_{ijkl} f_{ij} \tag{1b}$$

$$Min \sum_{i} \sum_{j} ST_{ij} \tag{1c}$$

Subject to:

$$\sum_{k} X_{ik} = 1 \qquad \forall i \in N \tag{2}$$

$$\sum_{i} X_{ik} \leq MH_k \qquad \forall k \in H \tag{3}$$

$$\sum_{k\in H} X_{kk} = P \tag{4}$$

$$\sum_{i} X_{ik} \leq MX_{kk} \qquad \forall k \in H \tag{5}$$

$$Z_{kl} \leq H_k \qquad \forall k, l \in H : k \neq l \tag{6}$$

$$Z_{kl} \leq H_l \qquad \forall k, l \in H : k \neq l \tag{7}$$

$$\sum_{l:l\neq k} Z_{kl} \geq 1 + M\left(X_{kk} - 1\right) \qquad \forall k \in H \tag{8}$$

$$\sum_{k,l:k\neq l} Y_{ijkl} = 1 - \hat{Y}_{ij} \qquad \forall i, j \in N : i \neq j \tag{9}$$

$$\sum_{l:l\neq k} Y_{ijkl} - \sum_{l:l\neq k} Y_{ijlk} = X_{ik} - X_{jk} \qquad \forall i, j \in N : i \neq j, k \in H \tag{10}$$

$$Y_{ijkl} + Y_{ijlk} \leq Z_{kl} \qquad \forall i, j \in N : i \neq j, k, l \in H, k \neq l \tag{11}$$

$$num_{kl} \geq \frac{TFM_{kl}}{cap} \qquad \forall k, l \in H : k \neq l \tag{12}$$

$$ICG_{kl} = num_{kl} CV \qquad \forall k, l \in H : k \neq l \tag{13}$$

$$TFM_{kl} = \sum_{i,j:i\neq j} f_{ij} Y_{ijkl} \qquad \forall k, l \in H : k \neq l \tag{14}$$

$$ST_{ij} = \sum_{k:k\neq i} tt_{ik} X_{ik} + \sum_{k,l:k\neq l,t} \left(ot_k + \alpha tt_{ij} + ot_l\right) Y_{ijkl} + \sum_{k:k\neq j} tt_{kj} X_{kj} + tt_{ij}\hat{Y}_{ij} \quad \forall i, j \in N : i \neq j \tag{15}$$

$$ST_{ij} \leq SB_{ij} \quad \forall i, j \in N : i \neq j \tag{16}$$

$$H_k \in \{0, 1\} \quad \forall k \in H \tag{17}$$

$$X_{ik} \in \{0, 1\} \quad \forall i \in N, k \in H \tag{18}$$

$$Z_{lk}^m \in \{0, 1\} \quad \forall k, l \in H : k \neq l \tag{19}$$

$$Y_{ijkl} \in \{0, 1\} \quad \forall i, j \in N : i \neq j, k, l \in H : k \neq l \tag{20}$$

$$\hat{Y}_{ij} \in \{0, 1\} \quad \forall i, j \in N : i \neq j \tag{21}$$

$$TFG_{kl} \geq 0 \quad \forall k, l \in H : k \neq l \tag{22}$$

$$num_{kl} \geq 0 \quad \forall k, l \in H : k \neq l \tag{23}$$

$$ICG_{kl} \geq 0 \quad \forall k, l \in H : k \neq l \tag{24}$$

$$TFM_{kl} \geq 0 \quad \forall k, l \in H : k \neq l \tag{25}$$

$$ICM_{kl} \geq 0 \quad \forall k, l \in H : k \neq l \tag{26}$$

$$ST_{ij} \geq 0 \quad \forall i, j \in N : i \neq j \tag{27}$$

The first objective function includes six parts; the first part shows the fixed cost of establishing the hub, the second part is related to the cost of establishing the inter-hub infrastructure, the third part is associated with the direct transportation cost of the equipment, and the fourth, fifth and sixth parts are related the transportation cost of the hub network.

The second objective function minimises the amount of environmental pollution caused by transportation between stations. The first term minimises biological pollution and the second term minimises noise pollution. Biological and noise pollutions are not a function of cost and are presented separately in the second objective of the proposed model. Also, the parameters are estimated by using the methods proposed by Mohammadi et al. (2014) and Zhalechian et al. (2017).

The third objective function also minimises the total transportation time between stations. It is obvious that the shorter the shipping time, the more favourable it is for the customers. Therefore, this objective function is known as the social aspect of sustainable development.

Constraint (2) states that each non-hub station can be assigned to only one hub.

Constraints (3) and (4) establish the relationship between the two types of facility establishment variables.

Constraint (5) indicates that a node can be assigned to a hub when the desired hub is established.

Constraint (6) shows that an inter-hub connection can be formed when both nodes are selected as hubs.

Constraint (7) states that two hubs are linked by establishing two hubs in two points.

Constraint (8) indicates that if a point is selected as a hub, it will definitely be linked to another hub with inter-hub connection.

Constraint (9) shows that the selection is made based on hub and direct transportation.

Constraint (10) states which inter-hub connection should be used for transportation between two stations.

Constraint (11) ensures that the flow of wagons takes place only through the inter-hub connections.

Constraint (12) determines the number of required locomotives.

Constraint (13) computes the inter-hub transportation cost.

Constraint (14) calculates the total number of the wagons transported between the hubs.

Constraint (15) determines the total service time between two stations and constraint (16) specifies the corresponding bound.

Constraints (17) to (28) defines the value ranges of the model decision variables.

3.5 Solution approach

In solving multi-objective optimisation problems, instead of having an optimal solution, there is a set of solutions called optimal Pareto front. Various methods have been presented to discover the optimal Pareto set, among which the augmented epsilon constraint (AEC) method is more efficient. Suppose an overall multi-objective optimisation model as follows.

$$
\begin{aligned}
&\max\left(f_1(x), f_2(x), \dots, f_p(x)\right) \\
&\text{s.t.} \\
&x \in S
\end{aligned}
\tag{29}
$$

where x is the vector of decision variables, $f_1(x)$, $f_2(x)$, …, $f_p(x)$ are the objective functions, and S is the feasible region. According to the structure proposed by Mavrotas and Florios (2013) for finding optimal Pareto solutions, the model (29) is transformed into the following model:

$$
\begin{aligned}
&\max\left(f_1(x) + eps \times \left(\frac{s_2}{r_2} + 10^{-1} \times \frac{s_3}{r_3} + \ldots + 10^{-(p-2)} \times \frac{s_p}{r_p}\right)\right) \\
&\text{s.t.} \\
&f_2(x) - s_2 = e_2 \\
&f_3(x) - s_3 = e_3 \\
&\vdots \\
&f_p(x) - s_p = e_p \\
&x \in S \\
&s_i \in R
\end{aligned}
\tag{30}
$$

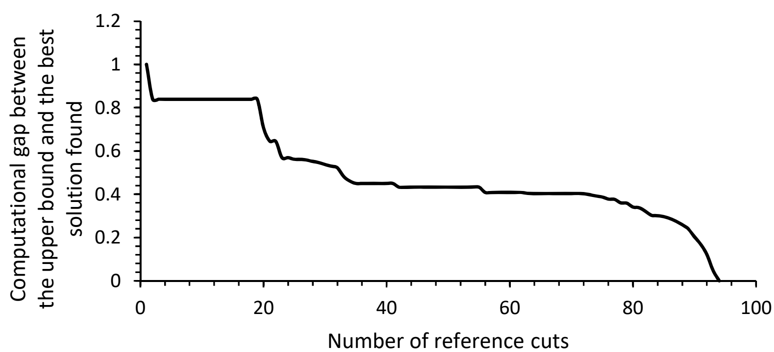
3.6 Computational results

In this section, the computational results obtained from the implementation of the proposed model in a problem of intercity train repair management are provided. For this purpose, it is assumed that there is a railway network with ten stations, where stations 1, 4, 6, 8 and 10 are potentially considered as the repair centres. It should be noted that these stations are the collection centres for defective wagons. The problem data are presented in Appendix Table A1–A11.

It is also assumed that the time discount coefficient (α) is equal to 0.206. Also, the capacity of trains to carry repaired wagons (*Cap*) is equal to 20, and the cost of using a locomotive to carry wagons (*CV*) is equal to 50. In the related studies, the value of α has been considered a random number between 0 and 1 (Zhalechian et al., 2017). In this research, this value was set to 0.206 using a random uniform distribution function.

After solving the problem with the GAMS software using the CPLEX solver, the descending graph of the computational gap between the upper bound and the best solution found in each cut is shown in Figure 1.

Figure 1 Graph of the computational gap between the upper bound and the best solution found in each cut



As can be seen in Figure 1, in the computational gap between 60% and 40%, the reducing trend is very slow and a large number of cuts is required which shows the high complexity of the model. It should be stated that the global optimal solution was found within 1 minute and 35 seconds. The results are presented in Table 2.

Table 2 Objective function value

The total value of the objective function ($)	*First part ($)*	*Second part ($)*	*Third part ($)*	*Forth part ($)*	*Fifth part ($)*	*Sixth part ($)*
144,331	13,961	10,734	53,778	11,262	2,950	51,636

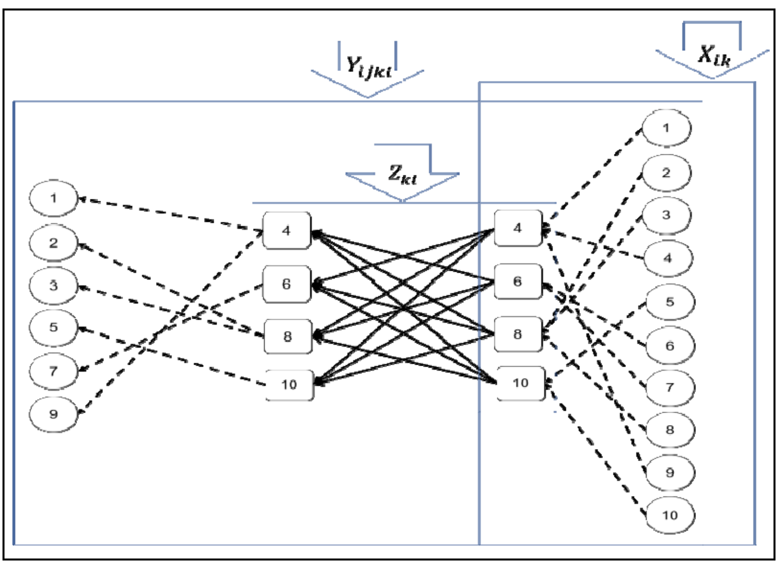
Considering the volume of wagons' flow between stations, it is necessary to establish a large number of hubs. Therefore, the available hubs (H_k) include stations 4, 6, 8 and 10. It is obvious that in some stations, direct transportation has been carried out, which are presented in Table 3.

It is clear that the transport between other stations has been carried out through the hub network. Therefore, the flow between hubs is investigated in the following.

Table 3 Stations with direct transportation between each other

	Station									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Station 1				✓					✓	
Station 2			✓					✓		
Station 3		✓						✓		
Station 4	✓								✓	
Station 5										✓
Station 6							✓			
Station 7						✓				
Station 8		✓	✓							
Station 9	✓			✓						
Station 10					✓					

Figure 2 Flow between hubs and allocation in the rail freight network (see online version for colours)



The values of the X_{ik} variable are presented in Table 4.

Table 4 Allocation of the stations to the established hubs

	Station									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Station (hub) 4	1			1					1	
Station (hub) 6						1	1			
Station (hub) 8		1	1					1		
Station (hub) 10					1					1

Table 5 The structure created for the inter-hub network

	Station (hub) 4	*Station (hub) 6*	*Station (hub) 8*	*Station (hub) 10*
Station (hub) 4	0	1	1	1
Station (hub) 6	1	0	1	1
Station (hub) 8	1	1	0	1
Station (hub) 10	1	1	1	0

Table 6 Number of required locomotives between two stations (num_{kl})

	Station 4	*Station 6*	*Station 8*	*Station 10*
Station 4	0	6	8	5
Station 6	4	0	5	3
Station 8	9	3	0	3
Station 10	5	3	5	0

Table 7 The total number of wagons transported between hubs (TFM_{kl})

	Station 4	*Station 6*	*Station 8*	*Station 10*
Station 4	0	104	146	84
Station 6	68	0	92	51
Station 8	179	46	0	55
Station 10	82	45	93	0

Table 8 Transportation time of wagons between two stations (ST_{ij}) (min)

	Station									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Station 1	0	93.355	121.064	0	88.355	99.473	93.236	117.064	0	101.591
Station 2	101.473	0	0	115.827	91.355	98.355	108.591	0	103.473	92.236
Station 3	115.827	0	0	121.945	93.355	116.827	118.827	0	113.709	102.473
Station 4	0	105.591	100.355		100.591	99.355	117.827	92.236	0	122.064
Station 5	102.709	101.709	112.945	104.709		111.945	93.355	92.473	108.827	0
Station 6	126.182	125.182	124.064	107.591	103.709	0	0	95.355	115.827	116.945
Station 7	111.827	90.236	117.945	101.473	97.591	0	0	109.827	109.709	110.827
Station 8	123.182	0	0	125.182	117.182	99.473	105.591	0	96.355	113.945
Station 9	0	113.945	112.827	0	108.945	91.236	122.064	88.236	0	101.591
Station 10	115.945	102.591	109.709	105.591	0	121.064	110.709	97.473	109.709	0

As can be seen in Table 4, according to the constraint (2) of the proposed mathematical model, each station is assigned to only one hub. Also, according to the constraint (5), each station is assigned to the hub established in the same station.

Subsequently, the values of the Z_{kl} variable are shown in Table 5.

The number of required locomotives between two stations is as shown in Table 6.

Other information related to the cost of moving between hubs, the total number of wagons transported between hubs and finally the transportation time between hubs are presented in Tables 7 and 8.

As can be seen, the obtained solutions are feasible, which demonstrates the validity and performance of the proposed model.

3.7 Sensitivity analysis

In this section, the sensitivity analysis is performed to investigate the consequence of changing the values of the model parameters on the results. For this purpose, three important parameters of the mathematical model, which are expected to have the greatest effect on the results, have been selected to analyse the changes in the values of these parameters in different conditions. It should be noted that the results of changing the aforementioned parameters on the values of different parts of the objective functions, the number of established hubs, the number of vehicles used, and the number of routes in the hub network are investigated.

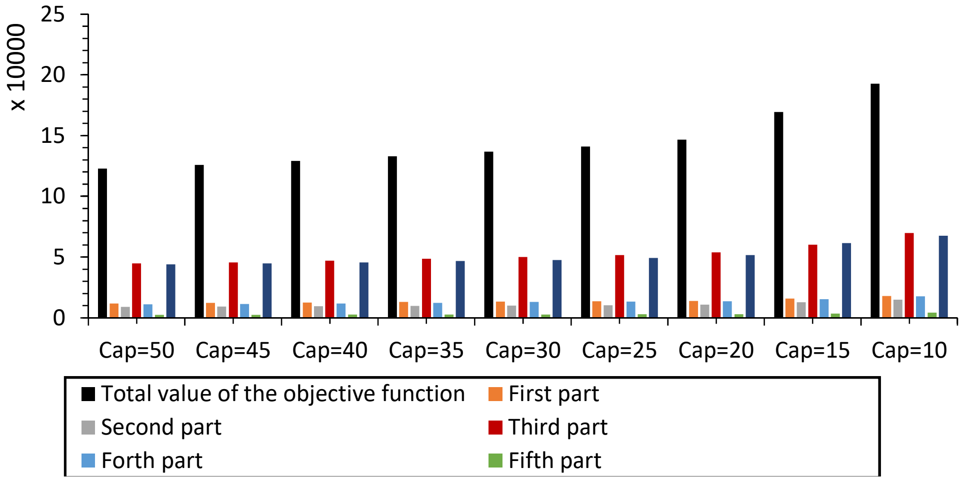
3.7.1 Analysis of changes in the carrying capacity of wagons (Cap)

As the main goal of this research is to develop the use of hub-based networks for facilitating the flow management in the railway networks of the country, the carrying capacity of wagons in the routes between the hubs can have a significant impact on the results. Therefore, in this section, the effect of changing the capacity level on the results is investigated considering ten different conditions. The findings are presented in Table 9.

Table 9 Effect of changing the capacity on the values of the different parts of the objective function

Capacity (ton)	*Total value of the objective function ($)*	*First part ($)*	*Second part ($)*	*Third part ($)*	*Forth part ($)*	*Fifth part ($)*	*Sixth part ($)*
Cap = 50	122,933	11,629	8,940	44,793	11,237	2,433	43,901
Cap = 45	125,806	12,113	9,216	45,707	11,466	2,508	44,796
Cap = 40	129,100	12,487	9,404	47,120	11,820	2,559	45,710
Cap = 35	133,047	13,007	9,898	48,577	12,312	2,611	46,642
Cap = 30	136,751	13,272	10,100	50,079	12,959	2,748	47,593
Cap = 25	140,870	13,682	10,412	51,627	13,223	2,862	49,064
Cap = 20	146,561	13,961	10,734	53,778	13,492	2,950	51,646
Cap = 15	169,380	15,916	12,881	60,232	15,381	3,511	61,459
Cap = 10	192,553	17,986	15,071	69,870	17,842	4,179	67,605

Figure 3 Effect of changing the capacity on the values of the different parts of the objective function (see online version for colours)



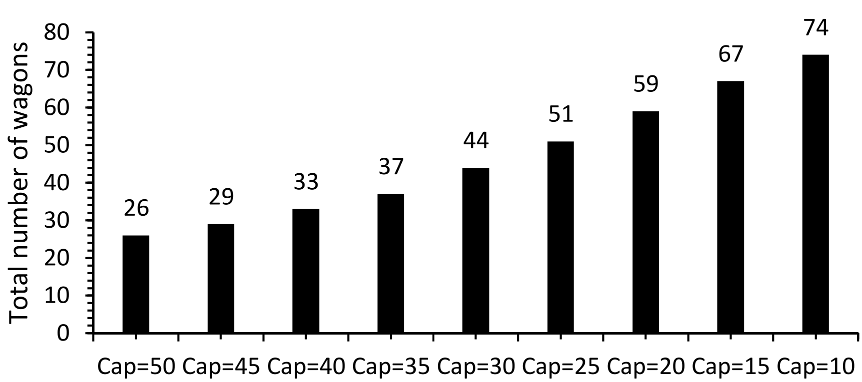
As can be seen in Table 9, with the increase of the capacity value, the values of the different parts of the objective function decrease. Of course, this matter is exactly in line with reality; as if the capacity is increased, fewer vehicles will be needed, therefore, the costs will be reduced (shown in Figure 3).

In addition, Table 10 exhibits the effect of changing the capacity on the total number of required vehicles.

Table 10 Effect of changing the capacity on the number of required vehicles (num_{kl})

Capacity (ton)	*Number of vehicles*	*Capacity (ton)*	*Number of vehicles*
Cap = 50	26	*Cap* = 25	51
Cap = 45	29	*Cap* = 20	59
Cap = 40	33	*Cap* = 15	67
Cap = 35	37	*Cap* = 10	74
Cap = 30	44		

Figure 4 Total number of required locomotives based on capacity



It is clear that increasing the capacity leads to decreasing the number of locomotives. In fact, the higher the carrying capacity of the wagons, the easier it is to manage the flow between the hubs and transfer directly, therefore, the number of locomotives is reduced. Figure 4 depicts the changes in the total number of locomotives in response to changes in the capacity.

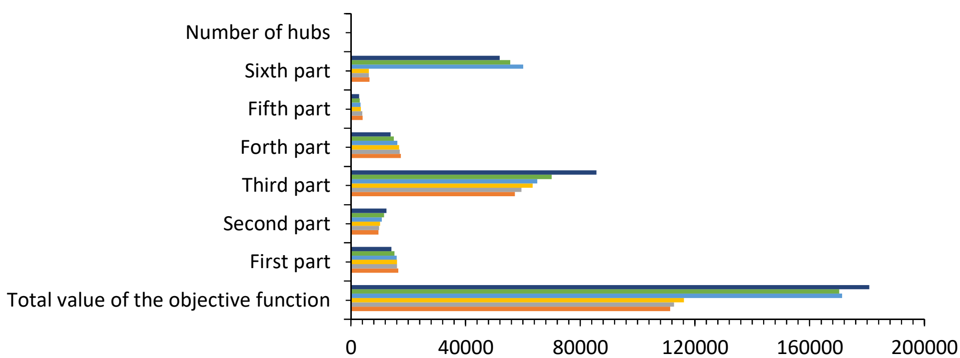
3.7.2 Analysis of changes in the cost of establishing inter-hub infrastructures (HL_{kl})

One of the most important costs in transportation planning in hub networks is the cost of establishing the necessary infrastructure for the communication development in this type of networks. Hence, in this section, the effects of increasing and decreasing this cost on the values of the objective function as well as the number of established hubs are investigated. For this purpose, the impacts of the changes in the cost of inter-hub network in the range of ±20%, ±40%, and ±60% (increase/decrease) are analysed and the results are provided in Table 11.

Table 11 Impacts of the changes in the cost of inter-hub infrastructures (HL_{kl}) on the values of different parts of the objective function

	Changes (HL_{kl}) (\$)	*Total value of the objective function (\$)*	*First part (\$)*	*Second part (\$)*	*Third part (\$)*	*Forth part (\$)*	*Fifth part (\$)*	*Sixth part (\$)*	*Number of hubs*
Decrease	60%	111,322	16,475	9,654	57,197	17,459	4,125	6,412	6
	40%	112,659	16,127	9,834	59,411	17,053	3,966	6,268	5
	20%	116,124	16,127	10,184	63,317	16,845	3,457	6,194	5
Increase	20%	171,351	15,962	10,783	65,008	16,145	3,337	60,116	4
	40%	170,321	15,193	11,549	70,040	14,928	3,026	55,585	3
	60%	180,720	14,182	12,370	85,597	13,802	2,879	51,890	2

Figure 5 Effect of changing the cost of establishing inter-hub infrastructures on the values of the different parts of the objective function (see online version for colours)



As can be seen in Table 11, the cost of the whole system is affected by the increase/decrease of the cost of establishing infrastructure. It should be noted that the values of different parts of the objective function have also been increased/decreased, which indicates the great impact of this parameter on the model. It is expected that with the increase or decrease of the cost, the number of selected hub centres will decrease or increase, therefore, the whole flow of wagons in the network will be changed. Figure 5 depicts these changes.

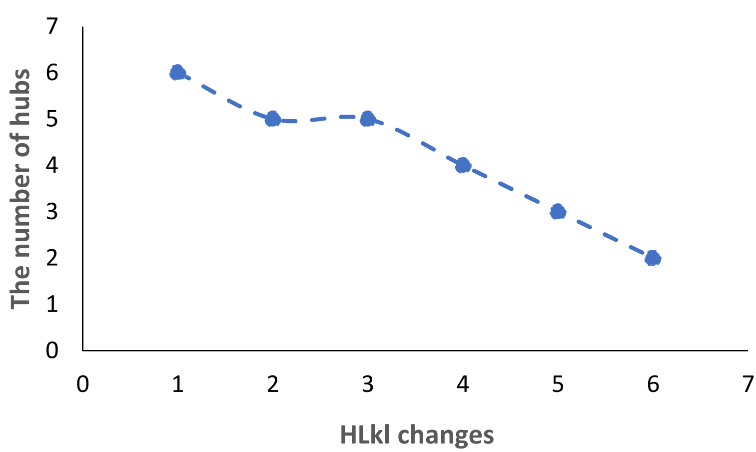
It can be stated that increasing or decreasing the value of the HL_{kl} parameter leads to the number of hubs decrease or increase. This trend is shown in Table 12 and Figure 6.

Table 12 Effect of changing the cost of establishing inter-hub infrastructures on the number of hubs

	Changes in HL_{kl} ($)	*Number of hubs*
Decrease	60%	6
	40%	5
	20%	5
Increase	20%	4
	40%	3
	60%	2

It can be seen in Table 12 that the number of hubs has always decreased or increased, which demonstrates the right performance of the model as expected. Figure 6 clearly depicts this trend.

Figure 6 Changes in the number of established hubs according to the incremental value of the parameter HL_{kl} (see online version for colours)



3.7.3 Analysis of changes in the flow between points (demand)

In this section, the changes in the model through increasing/decreasing customer demand are examined. For this purpose, ten different demand levels are considered and the results are presented in Table 13.

As can be seen in Table 13, the changes in demand (decrease and increase) can directly and affect the entire system. In fact, through demand controlling and its accurate forecasting, the total costs will be reduced.

In this part, four scenarios with different values for the demand parameter are considered as shown in Table 14.

The changes in the objective function value are depicted in Figure 7.

As can be seen in Figure 7, with changes in demand, the value of the objective function and the number of locomotives change, which demonstrates the considerable impact of this parameter on the results.

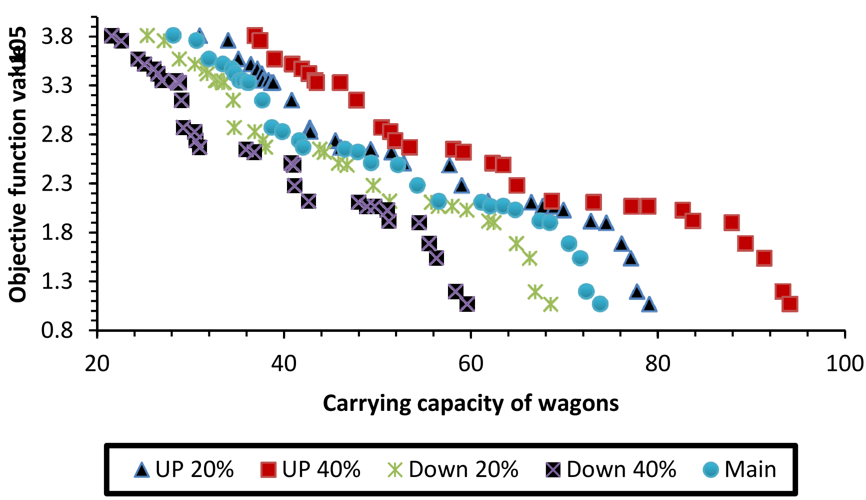
Table 13 Impact of demand changes on the results

Demand changes (ton)	*Established hubs*	*Number of locomotives used*
–50%	2	14
–40%	2	14
–30%	3	14
–20%	3	23
–10%	3	23
+10%	4	23
+20%	4	31
+30%	4	31
+40%	5	31
+50%	5	31

Table 14 Four scenarios with different demand levels

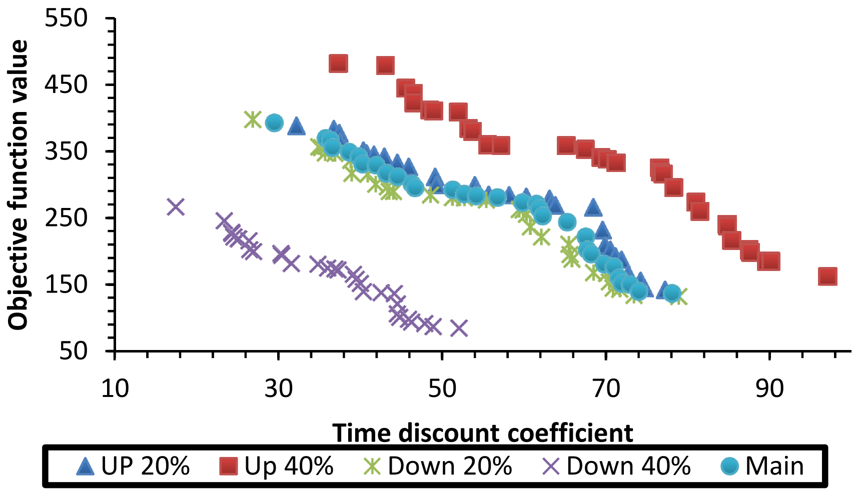
First scenario	*Second scenario*	*Third scenario*	*Forth scenario*
–40%	–20%	+20%	+40%

Figure 7 Changes in the objective function value and the carrying capacity of wagons based on the demand changes (see online version for colours)



In the following, the demand parameter and time discount coefficient are changed according to the defined scenarios to investigate their effects on the value of the objective function (shown in Figure 8).

Figure 8 Changes in the objective function value in accordance with different values of demand and time discount coefficient (see online version for colours)



3.8 *Multi-objective mathematical model validation*

In this section, the multi-objective model is analysed. The second objective function deals with the minimisation of the environmental effects including the detrimental impacts of biological and noise pollution. The values of these two parameters are presented in Tables 15 and 16. It should be noted that the values of these parameters are between zero and one.

Table 15 The amount of biological pollution caused by transportation between two stations (EV_{ij}) (kg-CO_2/km)

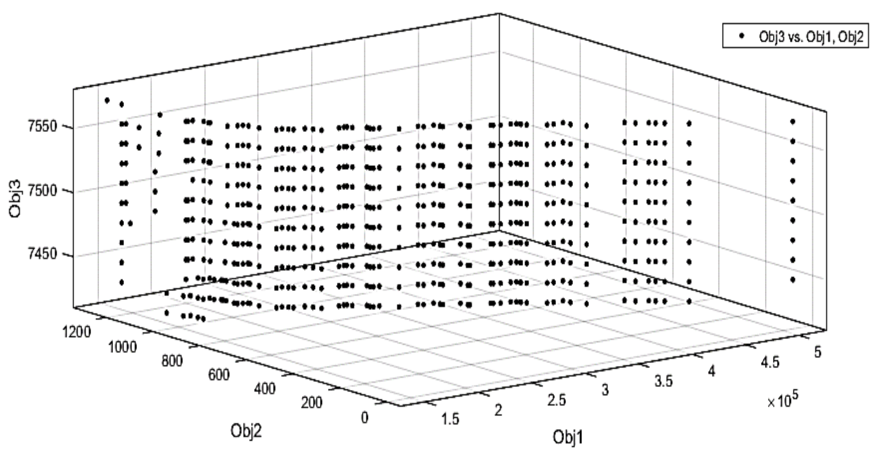
					Station					
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*Station 10*
Station 1	0	0.26	0.08	0.46	0.01	0.36	0.46	0.53	0.08	0.43
Station 2	0.26	0	0.52	0.15	0.11	0.24	0.19	0.6	0.5	0.02
Station 3	0.08	0.52	0	0.23	0.04	0.47	0.43	0.42	0.26	0.47
Station 4	0.46	0.15	0.23	0	0.39	0.31	0.04	0.51	0.13	0.28
Station 5	0.01	0.11	0.04	0.39	0	0.46	0.01	0.03	0.29	0.34
Station 6	0.36	0.24	0.47	0.31	0.46	0	0.59	0.53	0.07	0.47
Station 7	0.46	0.19	0.43	0.04	0.01	0.59	0	0.23	0.23	0.42
Station 8	0.53	0.6	0.42	0.51	0.03	0.53	0.23	0	0.47	0.11
Station 9	0.08	0.5	0.26	0.13	0.29	0.07	0.23	0.47	0	0.51
Station 10	0.43	0.02	0.47	0.28	0.34	0.47	0.42	0.11	0.51	0

Table 16 The amount of noise pollution caused by transportation between two stations (ES_{ij}) (db)

	Station									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Station 1	0	0.27	0.34	0.21	0.1	0.09	0.47	0.43	0.08	0.01
Station 2	0.27	0	0.6	0.6	0.15	0.17	0	0.49	0.14	0.38
Station 3	0.34	0.6	0	0.34	0.56	0.33	0.19	0.51	0	0.59
Station 4	0.21	0.6	0.34	0	0.47	0.08	0.31	0.04	0.33	0.43
Station 5	0.1	0.15	0.56	0.47	0	0.16	0.31	0.22	0.42	0.16
Station 6	0.09	0.17	0.33	0.08	0.16	0	0.11	0.09	0.3	0.21
Station 7	0.47	0	0.19	0.31	0.31	0.11	0	0.27	0.14	0.19
Station 8	0.43	0.49	0.51	0.04	0.22	0.09	0.27	0	0.53	0.42
Station 9	0.08	0.14	0	0.33	0.42	0.3	0.14	0.53	0	0.35
Station 10	0.01	0.38	0.59	0.43	0.16	0.21	0.19	0.42	0.35	0

It should be noted that the values of the other parameters are the same as the first numerical example. After solving the problem with the epsilon constraint method, 597 Pareto solutions were obtained, depicted in Figure 9.

Figure 9 Diagram of the Pareto front obtained by solving the multi-objective mathematical model considering the numerical example



3.9 Analytical comparison of the proposed model

It should be noted that the obtained solutions for the multi-objective model are non-dominant. Therefore, the analysis of the multi-objective models is not as easy as single-objective models. To this end, it is necessary to use the criteria for comparison. In this research, the MID index is taken into consideration. The MID index calculates the Euclidean distance between the non-dominant solutions according to the following equation.

$$MID = \frac{\sum_{i=1}^{|Q|} \left(\sqrt{\sum_{j=1}^{n_{obj}} \left(\frac{f_i^j - f_{best}^j}{f_{\max}^j - f_{\min}^j} \right)^2} \right)}{|Q|} \tag{31}$$

where f_i^j represents the i^{th} solution and the j^{th} objective function. Also, f_{best}^j is the ideal point for the j^{th} objective function and $f_{\max}^j$ and $f_{\min}^j$ are respectively the highest and lowest values among all Pareto solutions for the j^{th} objective function. |Q| denotes the number of points in the Pareto optimal front and n_{obj} is the number of objective functions. Figure 10 shows the conceptual view of the MID index.

It should be mentioned that in order to further analyse the results, different values of demand changes, which are shown by the symbol (*bal*), are considered in different values of 0.2, 0.3 and 0.35. The results are presented in Table 17.

Figure 10 Conceptual view of MID (see online version for colours)

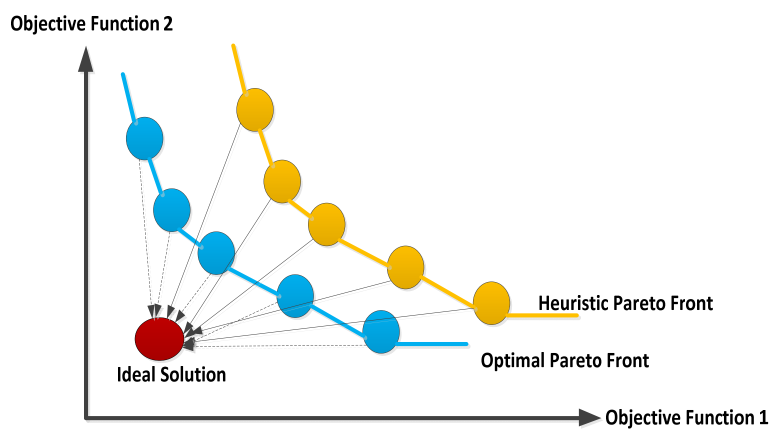
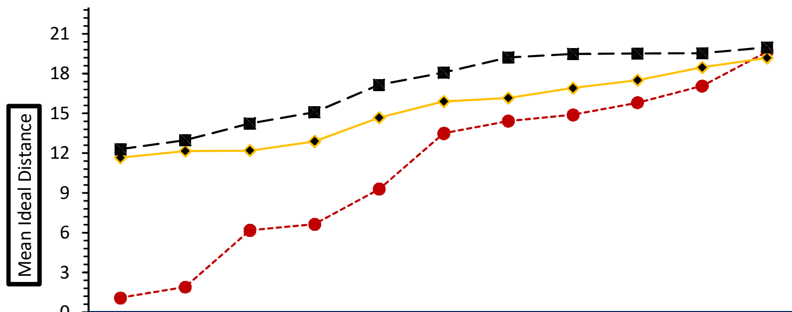


Table 17 Comparing the results of solving the mathematical model

Wagon capacity (ton)	*bal = 0.2*	*bal = 0.3*	*bal = 0.35*
		MID	
Cap = 50	1.1	11.66	12.31
Cap = 45	1.901	12.16	12.99
Cap = 40	6.18	12.19	14.24
Cap = 35	6.64	12.89	15.08
Cap = 30	9.29	14.68	17.15
Cap = 25	13.49	15.9	18.08
Cap = 20	14.42	16.16	19.22
Cap = 15	14.89	16.91	19.48
Cap = 10	158	17.5	19.51

It can be seen in Table 17 that the Pareto front does not change in case of the large-capacity wagons. But the situation is different in the case of low-capacity wagons. Figure 11 depicts the trend of MID changes for different *bal* values.

Figure 11 Changes in the MID values in accordance with different *bal* values (see online version for colours)



	N10P3 D2	N12P3 D2	N15P3 D2	N18P4 D2	N20P5 D3	N25P5 D3	N30P6 D3	N35P6 D3	N45P6 D3	N50P6 D3	N100P 10D5
bal=0.2	1.1	1.901	6.18	6.64	9.29	13.49	14.42	14.89	15.8	17.07	19.64
bal=0.3	11.66	12.16	12.19	12.89	14.68	15.9	16.16	16.91	17.5	18.47	19.18
bal=0.35	12.31	12.99	14.24	15.08	17.15	18.08	19.22	19.48	19.51	19.53	19.97

Table 18 Comparison of numerical results for the optimality gap of 10% and 15%

CPLEX optimality gap	*Instance code*	*bal = 0.2*	*bal = 0.3*	*bal = 0.35*
		MID gap%	*MID gap%*	*MID gap%*
10%	*Cap* = 50 (ton)	–3.14	–3.77	–2.16
	Cap = 45 (ton)	–1.77	0.14	1.22
	Cap = 40 (ton)	0.42	0.77	4.37
	Cap = 35 (ton)	1.22	1.96	6.94
	Cap = 30 (ton)	2.19	4.22	7.19
	Cap = 25 (ton)	5.54	6.17	7.86
	Cap = 20 (ton)	6.19	7.51	8.79
	Cap = 15 (ton)	4.22	8.22	9.19
	Cap = 10 (ton)	7.84	8.94	9.88
15%	*Cap* = 50 (ton)	–7.12	–6.19	–5.33
	Cap = 45 (ton)	–6.19	–4.11	–3.74
	Cap = 40 (ton)	–4.12	–4.01	–2.38
	Cap = 35 (ton)	–3.17	–3.97	–1.78
	Cap = 30 (ton)	–2.11	–1.45	0.28
	Cap = 25 (ton)	0.41	1.22	2.19
	Cap = 20 (ton)	0.36	1.37	3.67
	Cap = 15 (ton)	2.77	3.19	5.22
	Cap = 10 (ton)	3.16	4.01	6.77

It can be seen in Figure 11 that as the capacity decreases, the MID value increases in all *bal* values. The important point is that at the lowest capacity level, the MID value is almost equal for all *bal* values, because in this case, the solutions do not have a meaningful difference in different bal values.

In order to further examine the performance of the model in solving different numerical problems, the optimality gap of CPLEX is set as 10% and 15% and the results are analysed. This analysis demonstrates that the model can dominate the suboptimal solutions and is able to find the global optimal solutions. To this end, the aforementioned scenarios are re-implemented considering the optimality gap of 10% and 15% and the MID gap is analysed (shown in Table 18).

As can be seen, with the increase of the optimality gap, the value of the computational gap has decreased and in some cases it has become negative. The negative value indicates that the Pareto front is able to dominate the CPLEX solutions with optimality gaps of 10% and 15% and get closer to the ideal point, which demonstrates the proper performance of the model in finding the optimal Pareto front.

4 Managerial discussion

In the rail freight transportation, when a train is moving from the origin to the destination, a wagon may be damaged. If this damage is serious and it is not possible for the defective wagon to continue moving, the wagon must be removed from the train to carry out necessary repairs. In case of damaging wagons at the main station, the necessary repairs can be carried out. But there is not enough equipment at the transit stations. Ideally, all stations should have the necessary equipment to carry out repairs, which is not possible in the real world due to the large number of stations and the huge cost. Therefore, there are two scenarios, the first one is to send the wagons to the nearby main station for repair, and the second scenario is to bring the required equipment and team to that station. Carrying out repairs for each wagon is time-consuming and costly and causes delays. One of the primary solutions to this problem is to create proper transportation channels to collect broken wagons and send them to the nearest repair centre. It is also necessary to unload the defective wagons and deliver the goods to the customers by other trains.

This study formulates the repair and maintenance of freight wagons. The proposed model has some limitations in practical applications since the stations that have repair and maintenance centres are usually located at railway junctions. This makes it possible for all trains to access the maintenance and repair centres. In addition, this study focuses on the performance of repair centres for collecting and repairing defective wagons to reduce the downtime and delivery time. In addition, the proposed model of this research can be used to solve the problems of locating the place of maintenance and repairs of wagons in the rail transport and distribution network. In practice, this study will be of great help to rail transportation because wagon repair stations separate the defective wagon from the train to prevent the train from stopping. Also, in case of repairing the defective wagons, repairs will be made in the shortest possible time. In addition, this paper can provide a theoretical basis for research on the location of repair and maintenance centres in the rail distribution network, where goods are usually transported to the customer points via railways.

In addition, the courier and rail transport companies can apply the proposed model to minimise their total operational costs and environmental emissions; since the transportation cost is one of the fundamental factors in any transportation network, it can be said that if wagons with high capacities are used (of course, when the demand is high, in fact, the ratio between capacity and demand should be respected) the cost of the whole system will be reduced. It is obvious that with the increase in capacity, the number of locomotives will decrease. In fact, the higher the carrying capacity of the wagons, the easier it is to manage the flow between the hubs as well as the direct transfer, and therefore the number of locomotives will be reduced. On the other hand, carbon emissions directly affect the whole freight transportation network. For the sustainable development and decarbonisation of transportation, governmental and non-governmental organisations and should actively encourage transportation companies and couriers to expand their hub network. The reasonable arrangement of hub networks and a well-developed hub channel will encourage rail transport companies to adopt low-carbon modes of transportation. For the managers of transport companies, this study brought new inspirations from a low carbon perspective; considering carbon emissions can increase transportation time and affect the efficiency of cargo transportation. From the customers' viewpoint, managers should establish more maintenance centres to reduce the impact of high-carbon and inefficient transportation methods on customers. Therefore, this research provides insights to the managers of transportation companies in trading off between minimal carbon emissions, maximal customers' satisfaction, and maximal transportation company's benefits.

5 Conclusions

In this study, a multi-objective mathematical programming model was developed for the optimisation problem of managing the maintenance and repair of defective wagons in the rail hub logistics network. The use of railway hub stations results in reducing cost and service delivery time. The order integration channels as well as transportation between hubs reduce the operational costs of transportation and lead to close to optimal conditions. Considering the time discount coefficient in transportation between hubs has made the problem close to the real-world conditions since there are various examples in which consolidating shipments and managing transportation can reduce operational costs.

In other words, it can be said that in the present research, the design of the rail logistics hub network in the wagon maintenance and repair system has been studied as a mathematical optimisation problem with the aim of improving the management of the flow of goods between customer points. The EC method was utilised to solve the multi-objective model. It can be seen from the obtained results that the proposed model is capable of generating feasible and optimal global solutions. Also, according to the sensitivity analysis, increasing the capacity leads to decreasing the objective function value. In other words, if the capacity of wagons increases, the number of required vehicles and the associated costs will be reduced. In fact, the higher the carrying capacity, the easier it is to manage the flow between hubs and direct transportation, as a result, the number of vehicles will decrease. In addition, the cost of the entire system is affected by increasing/decreasing the cost of establishing infrastructure. It should be noted that the values of other parts of the objective function have also increased/decreased, which indicates the great impact of this parameter on the results. It is expected that with the cost increase or decrease, the number of selected hub centres will decrease or increase and therefore the entire transportation flow will be changed. In addition, increasing or decreasing the value of the HL_{kl} parameter leads to decreasing or increasing the number of hubs. Also, it has been concluded that with changes in demand, the values of the objective function and the number of vehicles have been changed, which demonstrates the considerable impact of this parameter on the results. Finally, with the increase of the time discount coefficient and demand changes, the value of the objective function has decreased and increased as expected, which shows the right performance of the proposed model in accordance with reality.

For further research, the following suggestions can be made. Different transportation modes including sea, land, and air should be considered in the model. As the network design problem is NP-hard, the heuristic algorithms can be exploited to solve large-size problems. Also, other methods such as data-oriented approach and possibilistic programming may be employed for dealing with uncertainty.

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Appendix

Table A1 Fixed cost of building infrastructure in repair stations (FH_k) ($)

Station 1	*Station 4*	*Station 6*	*Station 8*	*Station 10*
2,515	4,530	3,651	2,903	2,877

Table A2 Flow of wagons between two stations (f_{ij}) (ton)

	Station									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Station 1	0	10	26	2	15	30	17	30	23	4
Station 2	19	0	8	20	13	11	11	4	5	18
Station 3	25	7	0	23	9	3	15	5	26	8
Station 4	9	18	22	0	14	12	4	9	1	10
Station 5	5	19	17	23	0	20	23	19	9	3
Station 6	3	19	16	1	24	0	5	16	23	5
Station 7	1	18	19	12	11	7	0	4	28	11
Station 8	24	9	4	22	2	6	0	0	15	5
Station 9	5	10	10	10	29	30	11	11	0	12
Station 10	27	4	22	2	17	2	0	12	16	0

Table A3 Direct transportation cost between two stations ($\hat{C}_{ij}$) ($)

	Station									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Station 1	0	419	383	346	581	427	340	416	412	381
Station 2	585	0	389	322	420	331	415	397	358	334
Station 3	479	453	0	535	584	479	482	409	478	504
Station 4	452	348	497	0	337	596	368	503	533	580
Station 5	360	389	359	374	0	520	326	345	430	356
Station 6	508	529	346	417	509	0	484	593	308	356
Station 7	326	462	338	520	334	447	0	448	460	303
Station 8	463	435	593	355	349	307	353	0	305	551
Station 9	480	308	359	585	401	478	378	492	0	438
Station 10	418	542	462	417	467	580	405	302	585	0

Table A4 Normal transportation cost between two stations (C_{ij}) ($)

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

Table A5 Cost of forming a network between hubs (HL_{kl}) ($)

	Station 1	*Station 4*	*Station 6*	*Station 8*	*Station 10*
Station 1	0	937	832	866	863
Station 4	904	0	834	937	901
Station 6	915	944	0	804	968
Station 8	942	831	922	0	839
Station 10	873	925	946	883	0

Table A6 Cost of unloading and loading between hubs (d_{kl}) ($)

	Station 1	*Station 4*	*Station 6*	*Station 8*	*Station 10*
Station 1	0	30	68	69	69
Station 4	64	0	32	52	37
Station 6	70	62	0	33	47
Station 8	44	35	53	0	46
Station 10	67	39	39	52	0

Table A7 Cost of transportation between hubs (ICG_{kl}) ($)

	Station 4	*Station 6*	*Station 8*	*Station 10*
Station 4	0	300	400	250
Station 6	200	0	250	150
Station 8	450	150	0	150
Station 10	250	150	250	0

Table A8 Transportation time between stations (tt_{ij}) (min)

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

Table A9 Operation time at each hub station (ot_k) (min)

Station 1	*Station 4*	*Station 6*	*Station 8*	*Station 10*
3	1	2	2	1

Table A10 Time range for sending equipment between two stations (SB_{ij}) (min)

	Station									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Station 1	0	604	576	664	664	517	613	792	614	547
Station 2	642	0	562	688	501	651	501	656	751	522
Station 3	728	587	0	631	611	666	522	773	515	746
Station 4	738	698	618	0	760	793	672	594	637	611
Station 5	626	526	744	653	0	747	624	777	618	633
Station 6	709	703	671	552	681	0	718	574	543	767
Station 7	633	534	771	600	799	639	0	557	560	693
Station 8	740	676	791	647	612	748	746	0	778	501
Station 9	685	502	622	697	685	579	521	514	0	636
Station 10	551	671	758	511	607	601	646	578	767	0

Table A11 The distance matrix between stations (km)

	Station 1	*Station 2*	*Station 3*	*Station 4*	*Station 5*	*Station 6*	*Station 7*	*Station 8*	*Station 9*	*Station 10*
Station 1	0.00	4.00	5.01	4.99	4.56	2.09	1.52	5.50	1.78	1.03
Station 2	4.00	0.00	3.61	5.66	5.34	4.87	1.62	2.07	6.60	2.62
Station 3	5.01	3.61	0.00	2.82	4.77	4.36	4.85	1.21	3.28	4.00
Station 4	4.99	5.66	2.82	0.00	3.78	5.62	4.27	4.51	5.70	1.91
Station 5	4.56	5.34	4.77	3.78	0.00	2.79	1.19	4.73	2.80	2.05
Station 6	2.09	4.87	4.36	5.62	2.79	0.00	5.75	3.34	1.75	2.98
Station 7	1.52	1.62	4.85	4.27	1.19	5.75	0.00	3.15	5.49	2.90
Station 8	5.50	2.07	1.21	4.51	4.73	3.34	3.15	0.00	1.42	2.93
Station 9	1.78	6.60	3.28	5.70	2.80	1.75	5.49	1.42	0.00	6.78
Station 10	1.03	2.62	4.00	1.91	2.05	2.98	2.90	2.93	6.78	0.00