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RESEARCH PAPER

Dynamic Binary Mathematical Programming for Optimizing Freight Wagons Sizing, Case Study: The Railways of Islamic Republic of Iran

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Abstract

Managers and transportation planners have always paid special attention to rail transport and its development due to its high capacity and low shipping costs. In general, two solutions apply to the development of rail transit 1. deployment of new infrastructure and 2. improvement of existing conditions and procedures, which the second approach associated with a lower cost. This study proposes a dynamic binary mathematical programming model to formulate the existing rail freight procedures. Unlike previous studies, this paper uses a dynamic binary variable to express the wagon state (origin, destination, full or empty, and so on). Also, the current study proposes two simulation scenarios (FCFS: First Come First Served and SPT: Shortest Processing Time) for solving mathematical programming. In this paper, two different perspectives are considered 1. maximize the railway of the Islamic Republic of Iran (RAI) revenue and 2. maximize the rail transport companies' benefit. The main constraints are the loading /unloading capacity of stations, rail line capacity, and the capacity of locomotives to make up trains. Also, this study assumes that freight demand, travel time, and unloading /loading time are stochastic variables. In summary, this paper argued that the SPT strategy requires fewer wagons than FCFS, while the average productivity in SPT mode increases approximately by one unit, and unmet demand decreases. The results also show that the revenue of the rail freight companies in SPT strategy is more than FCFS strategy in all scenarios. Finally, based on the proposed model, it is determined that the service in the SPT strategy has better conditions than the FCFS strategy. The results of the models based on both views of RAI and rail freight companies indicate that all indicators' performance is similar. Comparing the results of the models with/without taking wagons maintenance into account shows that if the maintenance of wagons is considered, the numbers of required wagons will increase, productivity will decrease, average revenue per wagon of RAI and the average profit of rail freight transport companies will reduce.

Keywords:
Rail Freight Transportation;
Fleet Sizing;
Mathematical Programing

Introduction

The railway network is one of the vital infrastructures in most countries; because it has a significant capacity for carrying cargo and moving passengers. With high safety, high capacity,

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and reasonable price, freight transportation through the railway network has always been of particular interest to traders, artisans, managers, and planners. Therefore, the railway is always one of the main priorities of the country's government.

One of the most fundamental challenges of the planners of the railway transportation network has always been to determine the exact number of fleets required to meet customer demand. Please note that in this research, fleet means only wagons and locomotives. In the RAI network, the estimated size of the fleet is calculated by ordinary relationships that lead to fault. In these circumstances, If the number of wagons is higher than expected, some allocated wagons will remain useless, which will impose costs on RAI for each day of the idle wagon and cause waste of funds and the national budget. Otherwise, If the number of wagons is fewer than the required number, part of the demands won't be met and will often stay at the origin and arrive at the destination later, which will lead to customer dissatisfaction. Therefore, it is possible that due to these dissatisfactions, the demand for freight by rail will decrease, which will eventually lead to a decrease in the revenue of the RAI. On the other hand, the increased capacity will bring about much more demands, which will lead to revenue growth for RAI besides the profits of rail freight companies. On the other hand, increasing the capacity will attract more demand for rail freight, which will increase the revenue of PAI, as well as increase the profits of rail freight companies.

In Section 2, the most related research in the literature is briefly reviewed. In Section 3, this research methodology is discussed and the proposed dynamic Binary model is introduced. Then, in Section 4, analysis of outputs is described considering multiple scenarios to evaluate the results. Finally, the obtained results are presented in Section 5. Also, some suggestions for future studies are discussed in Section 6.

Literature review

In recent decades, various studies conducted to determine the fleet size, and each of them has looked at this issue from a different perspective. Some of the most important studies done in this field will be discussed as follow.

In 1961, Wyatt considered the simplest case of fleet sizing for shipping cargo. He assumed that the fleet is homogeneous and the capacity of the barges fluctuates in cycles. The purpose of his model was to minimize fixed and variable costs, the number of fleets available to the company, and the cost of renting the fleet [1]. Following the previous work, Mole introduced another model in 1975. In his model, the optimal fleet size depended on the time. he assumed demand forecasting was available for each period, and spending bi cost at period i increases the fleet capacity before period i+1. He proved that it was impossible to reduce the size of the fleet at the beginning of the period. Also, the capacity increase can be achieved by purchasing fleets [2]. One of the first studies in this field was done by Florian et al. in 1976. they proposed a model for determining the number of locomotives with the aim of minimizing maintenance costs. They assumed locomotives were heterogeneous; however, travel times between a specific origin and destination were fixed [3]. In 1977, Gertsbach and Gurevich proposed a model for determining the number of locomotives to minimize the size of fleets. In the proposed mathematical programming model, it assumed that locomotives are homogeneous and travel times are equal. They proved that a periodic schedule could be decomposed into an optimal periodic fleet [4]. Turnquist and Beaujon, in 1991, proposed an integrated model for fleet numbering and routing, which assumed that demands and travel times are uncertain and the fleet is homogeneous. The objective function of the model was to make a balance among the revenue of transporting loaded wagons, operating costs of the fleet, cost of owning the fleet, the cost of maintaining the wagons at the origins and destinations, and the penalty cost for unmet demands [5]. In 1997, Sherali and Tuncbilek designed static programming models and dynamic time-space models, as well as fleet management problem-solving algorithms. They developed models for determining the practical fleet sizing for the rail and automotive industries concerning the issue of transporting cars by wagons. The approach used was static and time-independent [6]. In 2000, Sherali and Maguire developed the dynamic mode of determining the size of a rail freight fleet for moving cars. They considered changes in demand and used the concept of a node and arrow and a planning horizon to describe their method [7]. In 2002 Bojovic, on the one hand, determined the optimal number of rail freight wagons to meet the demand and, on the other hand, minimized the total cost. He devised a new mathematical model based on the theory of optimal control. Uncertainty of travel time and the number of wagons sent from each station are input data and considered compatibility between wagon and cargo [8]. In 2003 List et al. examined the size of the fleet under uncertainty in demand and operating conditions. Their formulation focused on robust optimization, using a partial moment measure of risk. the risk measurement had incorporated into the expected recourse function of a two-stage stochastic programming formulation, and stochastic decomposition had been used as a solution procedure [9]. In 2007, Zhang and Li analyzed the problem of fleet sizing and routing in a multi-period and dynamic manner. The purpose is to determine the sequence of purchasing and leasing of the fleet and also to ascertain their number in a way that minimizes the total cost [10]. Sayarshad and Ghoseiri, in 2009, investigated the interaction among fleet sizing, productivity, and wagon allocation. It was supposed that wagon demands and travel times were definite. Also, unmet demands will be brought back and set equal to zero at the end of the planning period. The model provides rail network information such as marshaling yard capacity, unmet demands, number of full and empty wagons at any given time, and any place [11]. In 2011, Żak et al. proposed a multi-objective mathematical model for fleet sizing in road transport, taking into account the interests of stakeholders with a homogeneous fleet, in which formulated technical and economic constraints from a queuing theory point of view. In their model, in addition to the size of the fleet, they also included the optimization of technical support facilities for the maintenance and repair of trucks [12]. In 2015, Milenković et al. applied the Horizon Rolling approach to optimize and allocate fleet size simultaneously, assuming fleet heterogeneity for the rail industry. They developed a dynamic model by assuming the random variables of demand and travel time [13]. In 2016, Kallrath et al. presented a mathematical model to incorporate transport capacity in optimizing fleet sizing for chemical cargo. The model was designed from the point of view of the cargo owner, and constraints such as the structure of the network, alternative routes, train length, and weight are not considered [14]. In 2016, Mafakher et al. addressed the issue of using a multi-objective Simulated Annealing algorithm to solve the developed model for fleet sizing in the rail transport industry. They assumed demand and travel time as definite, and the objective function of the model sought to minimize delays in responding to demand [15]. In 2017, Razani and Yaghini proposed a mathematical programming model to determine the number of fleets required. They implemented their model on the condition of tank wagons. They also considered several service periods to improve the model results and used the freight company penalty method to avoid delays in responding to customer demand [16]. In 2017, Bachkar et al. used a probabilistic planning model to determine the optimal size of ethanol wagons for a given period. The research aimed to provide an innovative algorithm for policy-making to optimize the number of wagons required to carry ethanol. In the model, demand and travel times were considered uncertain and it was possible to buy and rent a wagon [17]. In 2019, Wang et al. addressed the issue of train formation in heavy railway networks. The research presented a binary mathematical programming model that minimizes the difference between the actual train arrival time and the expected [18]. In 2019, Hungerländer and Steininger dealt with the issue of determining the size of the fleet and the allocation of empty freight cars. In their study, they presented an integer mathematical programming model and considered different scenarios in terms of price, travel time, and demand to analyze the sensitivity of the model [19].

According to previous studies, it can be said that the decision variable is almost defined somehow shows the required number of fleets in each period. Integer programming has been used in former research. The main distinguishing feature of this study is the use of dynamic binary programming. So, freight wagons will be defined as an independent object that describes their characteristics such as full or empty, the origin and destination, and in transit or the depot state. As a result, accurate data of the fleet's status will be calculated for each wagon in all periods. Other contributions include the variability of freight demands and travel times and the application of simulation to solve the proposed model.

Methodology

The main objective of this research is to present a binary dynamic mathematical planning model to optimize the required number of cargo fleets. This paper considers two approaches for modeling to achieve this goal: (1) the view of the railways of RAI as the governing body and (2) rail freight transport companies as the private sectors. Also, this paper utilizes binary variables to develop a mathematical programming model where:

N indicates nodes (stations or repair centers) set

R indicates repair center set

i indicates origin (can be a station or a repair centers)

j indicates destination (can be a station or a repair centers)

l indicates locomotive mode of wagon (l is equal to the numeral of locomotive that pull wagon)

f indicates being full (f=1) or empty of wagon (f=2)

t indicates time periods

k indicates numeral of wagons

$\left(x_{fl}^{ij}\right)_{tk}$ is a binary decision variable that indicates state of wagon No. k in period t that dispatch from node i to node j with locomotive mode l in condition f.

$\left(L_{l}^{ij}\right)_{t}$ is a binary decision variable that indicates the state of locomotive No. l in period t that travels from node i to node j.

I_{fk}^{ij} indicates transportation cost of wagon No. K from origination i to destination j in mode f

Loc_{t}^{i} indicates locomotive inventory in destination i in period t

DW_{t}^{i} indicates wagon inventory in destination i in period t

PC_{ij} indicates critical capacity between station i and j

LC indicates locomotive capacity to hauling wagons

ISC_{i} indicates loading capacity at origin i

FSC_{j} indicates unloading capacity at destination j

RW_{t}^{j} indicates the number of wagons under repair in repair centers j at period t

IC_{fk}^{ij} indicates revenue of rail freight companies by hauling wagon No. K from origin I to destination j in mode f

CD indicates holding cost of stopped wagons in a depot

CR^{K} indicates maintenance costs of wagon No. K in a repair center

$$\max Z = \sum_{t,k}\left(\sum_{i\neq j} I_{fk}^{ij}\left(x_{lf}^{ij}\right)_{tk}\right) \tag{1}$$

or

$$\max Z = \sum_{t,k}\left(\sum_{i\neq j} IC_{fk}^{ij}\left(x_{lf}^{ij}\right)_{t,k}\right) - \sum_{i\neq j} I_{fk}^{ij}\left(x_{lf}^{ij}\right)_{t,k} - \sum_{j\in R} CR_k\left(x_{lf}^{ij}\right)_{t,k} - \sum_{i=j} CD\left(x_{lf}^{ij}\right)_{t,k} \tag{2}$$

Subjec to :

$$\sum\left(x_{lf}^{ij}\right)_{tk} = 1\ ;\ \forall(t,k) \tag{3}$$

$$\sum_{ij}\left(L_l^{ij}\right)_t = 1\ ;\ \forall(l,t) \tag{4}$$

$$\sum_{l\in Loc_t^i}\left(L_l^{ij}\right)_t = \min\left(\frac{D_t^{ij}}{LC}, \left|Loc_t^i\right|\right)\ ;\ \forall(t,i,j) \tag{5}$$

$$\sum_{fk}\left(x_{lf}^{ij}\right)_{tk} \le PC_{ij}\ ;\ \forall(t,l,i,j) \tag{6}$$

$$LC_{\min}\left(L_l^{ij}\right) \le \sum_{fk}\left(x_{lf}^{ij}\right)_{tk} \le LC\left(L_l^{ij}\right)_t\ ;\ \forall(t,l,i,j) \tag{7}$$

$$\sum_{k,f}\left(x_{fl}^{ij}\right)_{tk} \le ISC_i\ ;\ \forall(t,l,i,j) \tag{8}$$

$$\sum_{k,f}\left(x_{fl}^{ij}\right)_{tk} \le FSC_j\ ;\ \forall(t,l,i,j) \tag{9}$$

$$\sum_{jflk}\left(x_{lf}^{ji}\right)_{tk} - \sum_{jflk}\left(x_{lf}^{ij}\right)_{tk} + \left|DW_{t-1}^{i}\right| = \left|DW_t^{i}\right|;\ \forall t \tag{10}$$

$$\sum_{jl}\left(L_l^{ji}\right)_t - \sum_{jl}\left(L_l^{ij}\right)_t + \left|Loc_{t-1}^{i}\right| = \left|Loc_t^{i}\right|\ ;\ \forall t \tag{11}$$

$$\sum_{ilfk}\left(x_{lf}^{ij}\right)_{tk} - \sum_{ilfk}\left(x_{lf}^{ji}\right)_{tk} + RW_{t-1}^{j} = RW_t^{j}\ ;\ j\in R\ ,\ \forall t \tag{12}$$

$$\left(L_l^{ij}\right)_t\ is\ \text{binary} \tag{13}$$

$$\left(x_{lf}^{ij}\right)_{tk}\ is\ \text{binary} \tag{14}$$

Eq. 1 shows the objective function of the model that maximizes the revenue share (Track and locomotive share) of the RAI and Eq. 2 maximizes the profits of rail transport companies. These two equations will not run simultaneously and So, two mathematical models will be presented according to these two approaches. Eqs. 3 and 4 require that each wagon and locomotive must be in one position at a time. Eq. 5 Determines the required number of locomotives. Eq. 6 Indicates the technical limitations of the type of route that are effective in forming the train. Eq. 7 implies the capacity of locomotives and the minimum number of wagons to form a train. Eqs. 8 and 9 show loading and unloading capacity respectively. Eqs. 10 and 11 Indicates the inventory of wagons and locomotives at each station. Eq. 12 shows the number of wagons in each repair center and finally Eqs. 13 and 14 Indicate that the decision variables are binary.

In order to analyze the sensitivity of the proposed models to the maintenance constraints, the results of both models are analyzed in two cases with and without considering this limitation. to calculate the freight demand and travel time between stations i and j, as well as the loading and unloading time of trains, the following equations that are based on the normal distribution function, are used:

$$D_t^{ij} = N\left(D_{ave}^{ij}, \sigma_{dij}^2\right) \tag{15}$$

$$TT^{ij} = N\left(TT_{ave}^{ij}, \sigma_{TTij}^2\right) \tag{16}$$

$$TT_{\min}^{ij} \leq TT^{ij} \leq TT_{\max}^{ij} \tag{17}$$

$$TL_t^{i} = N\left(TL_{ave}^{i}, \sigma_{TLi}^2\right) \tag{18}$$

$$TL_{\min}^{i} \leq TL_t^{i} \leq TL_{\max}^{i} \tag{19}$$

$$TU_t^{j} = N\left(TU_{ave}^{j}, \sigma_{TUj}^2\right) \tag{20}$$

$$TU_{\min}^{j} \leq TU_t^{j} \leq TU_{\max}^{j} \tag{21}$$

in which, D_{ave}^{ij} and σ_{dij} , are mean and standard deviation of freight demands from i to j, respectively and TT_{ave}^{ij} and σ_{TTij} , , are mean and standard deviation of travel times between i and j, respectively. TL_{ave}^{i} and σ_{TLi} , , are mean and standard deviation of loading times of a wagon in Stations i, respectively and, TU_{ave}^{j} and σ_{TUj} are the mean and standard deviation of the unloading times of a wagon in station j, respectively.

Eq. 15 shows demand in period t and Eqs. 16 and 17 determine travel time between origin i and destination j and Eqs. 18 and 19 show the loading time at origin i and Eqs. 20 and 21 display unloading time at the destination station j.

This paper utilizes a proposed simulation method to solve the mathematical programming models. For this purpose, defines two different scenarios to simulate the freight transport process. In the first scenario, servicing of freight or unloading requests is done in the order of registered requests. Simply put, the sooner a train arrives at the station, the sooner it will be serviced (FCFS[†] scenario). In the second scenario, incoming trains are sorted from top to bottom according to the time required for service, and the train that requires the least time required for service is serviced (SPT[‡] scenario). It is worth mentioning that in this case, the order of arrival of trains to the station does not matter and the service time is the only criterion for prioritizing train service.

For a better summary, the proposed models are shown in Fig. 1. The flowchart of the proposed solution method to simulate the rail freight process is also illustrated in Fig. 2.

[†] First Come, First Served (FCFS)

[‡] Shortest Processing Time (SPT)

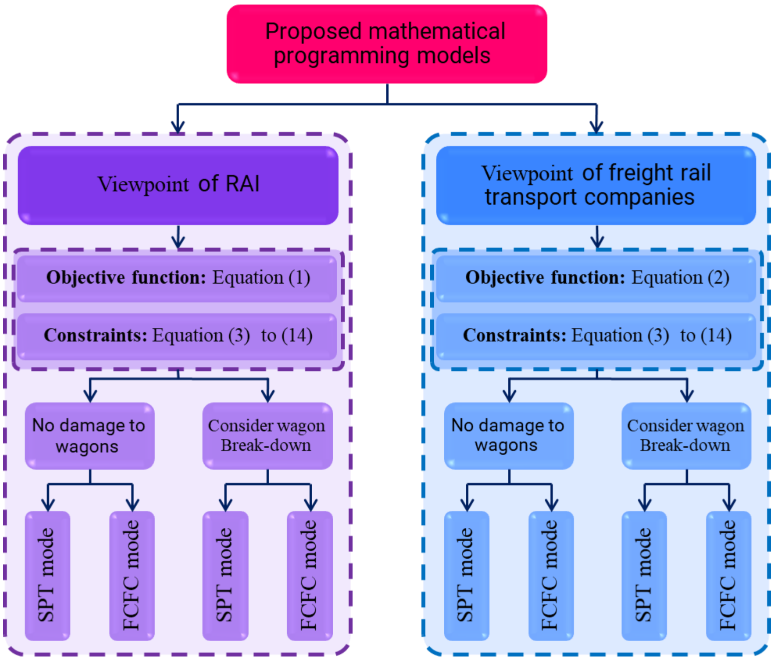

Fig. 1. Classification of proposed dynamic dual mathematical programming models

Discussion

For simulating process, mineral transport data of two routes, Chadormalo (Yazd) to Hasanabad (Isfahan) and Golgohar (Kerman) to Hasanabad (Isfahan), has been used (Fig. 3). According to the data received from RAI, the average daily demand for transporting iron ore in the form of concentrate powder from Chadormalo origin is 110 set 6-axis open-top wagons (with a standard deviation of 10) and from Golgohar origin is 50 set 4-axis open-top wagons (with a standard deviation of 5). Based on the operation tariff of RAI, if companies pay the transportation cost in cash, the right of access for loaded and empty wagons will be equal to 934 and 623 Rials per ton-kilometer, respectively. Also, this study utilizes Python Programming Language version 3.8.5 for simulating the proposed binary mathematical programming model [20].

The total demand from Chadormalo to Hasanabad in the hypothetical 30-day period is equal to 1508 wagons (average 50 wagons per day with a standard deviation of 10). Also, the demand from Gol Gohar to Hasanabad for the same period is equal to 3308 wagons (the average daily is 110 wagons with a standard deviation of 20). It is important to note that this demand will be the same for all modeling modes so that each model can be judged more accurately. Table 1 shows the results of all eight proposed models.

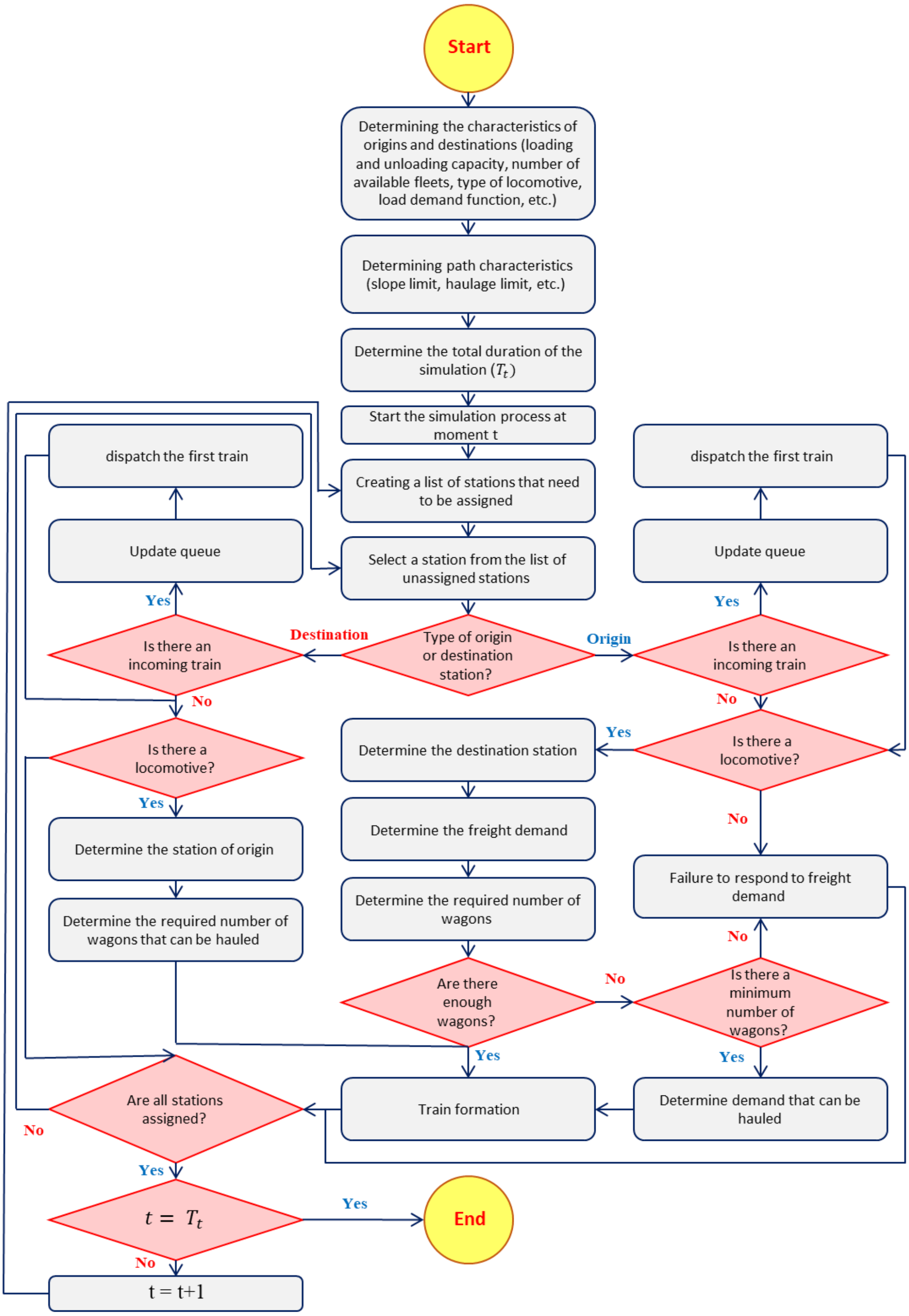

Fig. 2. Proposed flowchart to simulate the rail freight transport process

Fig. 3. Map of the studied routes used for simulation of the rail freight transport process

Table 1. Results of simulation of proposed mathematical programming models

Scenario	Number of wagons used (set)	Productivity coefficient	Met demand (wagon)	RAI Revenue (Billion Rials)	RAI Revenue per wagon (Million Rials)	Railway companies profit (Billion Rials)	Railway companies profit per wagon (Million Rials)
RAI No wagon breakdown FCFS	860	8.9	3842	303.63	353.1	-	-
RAI No wagon breakdown SPT	847	9.9	4182	333.05	393.2	-	-
RAI considering wagon breakdown FCFS	902	8.5	3821	302.4	335.3	-	-
RAI considering wagon breakdown SPT	876	9.4	4131	328.87	375.4	-	-
Railway Companies No wagon breakdown FCFS	859	9	3845	303.86	353.7	488.89	569.1
Railway Companies No wagon breakdown SPT	848	9.9	4186	333.28	393	543.35	640.7
Railway Companies considering wagon breakdown FCFS	927	8.2	3781	299.01	322.6	355.49	383.5
Railway Companies considering wagon breakdown SPT	859	9.4	4180	332.97	375.8	402.99	454.8

Description: Green represents the best value of the index and red represents the worst value of the index between different modeling scenarios.

Fig 4 shows the number of wagons carrying cargo between selected origins and destinations over a 30-day simulation period. The trends of different scenarios for the two viewpoints of RAI and private rail freight companies are almost similar. In both, the fleet size for models with wagons breakdown constraints is more than models without these constraints. On the other hand, it is pretty clear that the SPT service scenario, compared to the FCFS scenario, has fewer fleets sizes (between 1.5-7% in different scenarios).

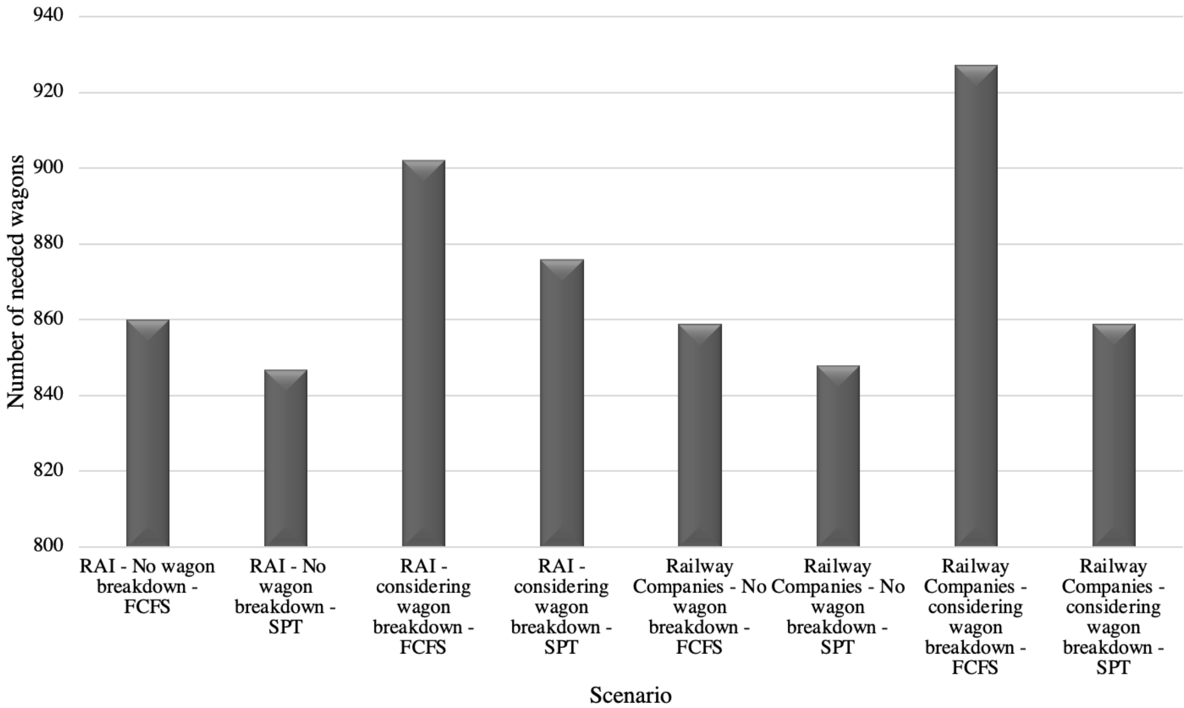

Fig. 4. Comparison of the number of freight wagons in each scenario

Fig 5 shows the productivity factor of wagons separately for different modeling scenarios over a 30-day simulation period. The trend of changes in the productivity factor is similar in two viewpoints of RAI and rail freight transport companies. On the other hand, the productivity coefficient is significantly reduced if the breakdown of wagons is considered (4.5-9%). Also, based on the results, the productivity coefficient will increase significantly if the SPT service mode is utilized to meet the demand (10-14.6%).

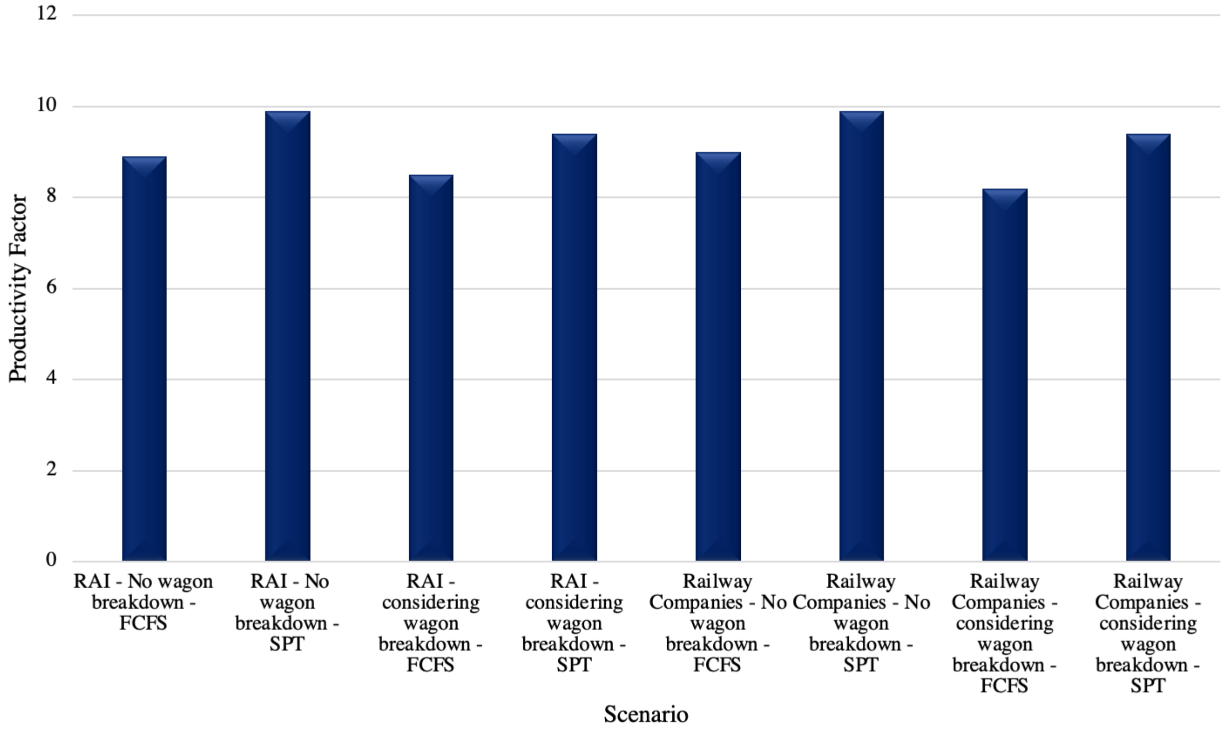

Fig. 5. Comparison of productivity of freight wagons in each scenario

Fig 6 shows the amount of met demand over a 30-day simulation period. The trend of all scenarios in both viewpoints of RAI and rail freight companies are similar. It is worth noting that if the breakdown of the wagons is considered, the fleet size will increase. In SPT scenarios compare to FCFS scenarios, the amount of the met demand will increase (about 10-10.5%).

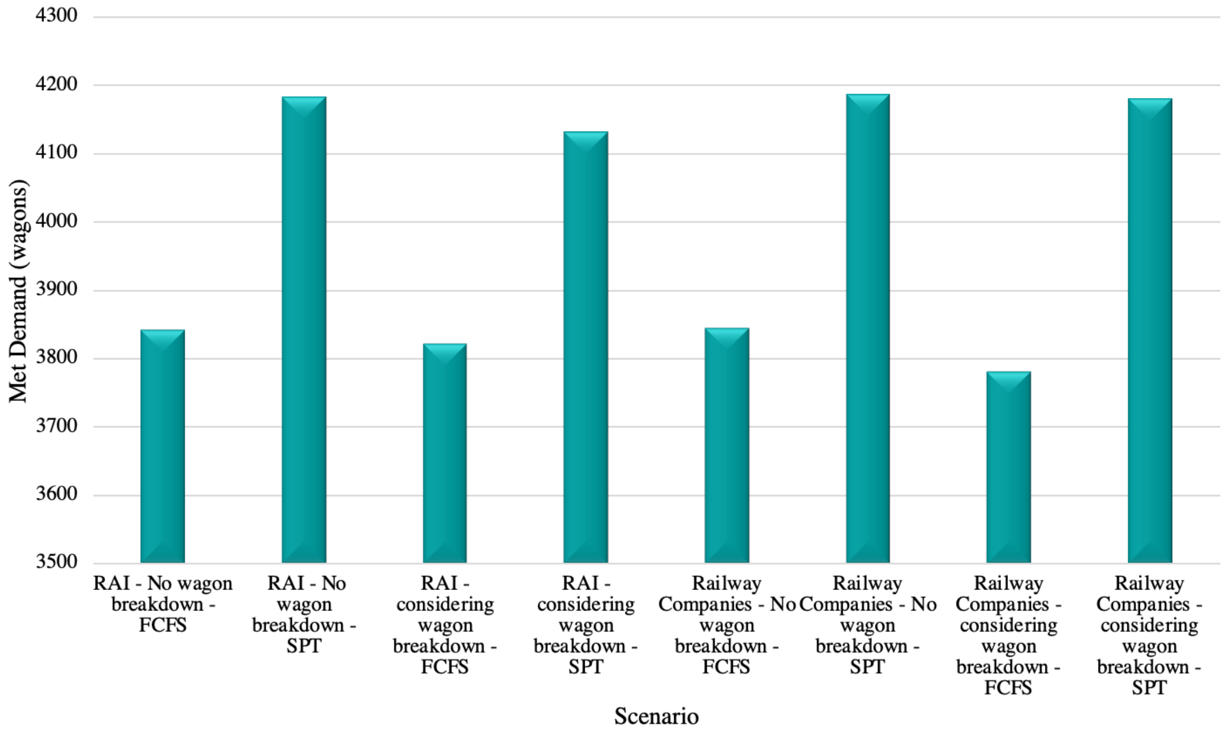

Fig. 6. Freight demand met in each scenario

Conclusion

Rail transport is one of the primary modes of freight transportation and passenger movement in all countries, especially developed countries. In Iran, the visionary development document pays special attention to this mode of transportation. There are various solutions for developing railway transportation. The development could include the construction of new rail lines and stations, the development of new facilities, the purchase of new fleets, and the optimization of cargo transportation processes. Some of these items, such as constructing new infrastructure or purchasing new fleets, require a significant amount of money. However, some approaches such as freight transport process optimization and the optimal use of the existing fleets have less cost than others.

Therefore, this study optimizes the number of required fleets and the rail freight transportation process. This paper utilizes a binary dynamic mathematical programming model to achieve this purpose. Previous studies have almost exclusively focused on utilizing integer programming. However, the decision variables of the proposed model are binary that describe the condition of each wagon at all times. Utilizing binary variables is one of the critical innovations of this research. Also, in the recommended mathematical model, the limitations of unloading and loading capacity of stations, route capacity, locomotive haulage capacity, train formation, and maintenance of wagons are considered.

This paper uses two different approaches to present the planning model. The first view is the view of RAI, which receives a transportation tariff from the railway companies to supply infrastructures in terms of ton-kilometers and type of cargo. In this case, the objective function of the proposed model is the maximization of RAI revenue. Another point of view is rail freight companies' view, whose purpose is the maximization of profits. These companies charge a fee to ship the cargo from the customer. The costs considered in this study are the right of access, fleet maintenance, and wagon stop at the depot. The amount of profit of these companies is equal to the difference between their income and expenses.

This study presents the results of proposed models with and without considering wagon breakdown constraints. In this paper, there are two scenarios for simulating the freight transport process. The First is FCFS service mode, and the second is SPT service mode. Also, the demand of freight transport between origins and destinations, travel time, and loading/unloading times are stochastic variables with normal distribution. The following are the most important results of the research:

- The results of the models in both approaches of RAI and rail freight companies indicate that all evaluation indices have similar performance.
- If proposed models include wagons breakdown constraints, the required fleet size will increase, the productivity factor will decrease, the average revenue of RAI per wagon will decrease, and the average profit of rail freight companies per wagon will decrease.
- In the SPT processing scenario, the productivity factor, the met demand, the average revenue of the RAI per wagon, and the average profit of the rail freight transport companies per wagon are higher than the FCFS processing scenarios. Also, the SPT scenario has less fleet size than the FCFS scenario. Therefore, it is clear that the SPT processing scenario is better than the FCFS scenario.

Suggestions and future works

According to the research results, the SPT service type has better conditions than the FCFS service mode in all studied indicators. Therefore authors suggest that RAI use the SPT mode to respond appropriately to freight transport demand.

This study did not consider capacity limitations for repair centers. Therefore, the authors suggest that for developing the proposed model and making it more realistic, the capacity of repair centers should be considered in future studies.

In the present study, due to the existing limitations, the damage of wagons and locomotives in transit was not considered. Therefore, the authors suggest providing a suitable mathematical planning model to optimize the management of the freight process in the case of wagons and locomotives breakdown in service.

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