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Greedy approach to railways network design based on least-cost block expansions - case study: Iran’s railways network

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ABSTRACT

Transportation problems are categorized into three levels: strategic, tactical, and functional, which have different level of budgets, level of decision makers, and horizon time. The problem of designing the rail network is one of the most important in the strategic level. In short, network design deals with how to allocate limited budget to expand the railway network infrastructure, in such a way that a certain objective function is optimized. The general form of the network design problem is a bi-level problem and falls in the category of NP-hard problems, which is difficult to solve even in small scales.

In this article, a heuristic algorithm is presented to solve the problem of network design aiming at minimization of total expansion costs in the network. In each iteration, the algorithm performs a traffic assignment and extracts the overcapacity blocks of the network. Having the list of overcapacity blocks available, in a greedy approach, the algorithm selects the block with the minimum expansion cost and marginally increases its capacity. The process of iterations as such continues until the entire amount of input demand is transferred. This algorithm is implemented in Java and applied to the Iran’s railways network as the case study. Given the inherent multiobjective nature of in the problem, we also report "pseudo-pareto" solutions for the problem based on the two measures of network throughput and expansion costs and discuss the obtained solutions.

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1. Introduction

Transportation is one of the most important factors in the growth and development of countries. Economists believe that no advanced economy can continue without paying attention to the modern transportation network, and transportation activities are among the most basic activities of economic growth. As one of the oldest methods of passenger and freight transportation, rail transportation is very popular in the world due to its unique features such as saving energy, compatibility with the environment, sustainable development, cost reduction, and greater security and safety than other modes of transportation. That is why governments are also taking their policies to strengthen rail transportation systems.

In today's world, cheap, fast, and easy freight transportation is considered one of the underpinning development factors of the countries. For this purpose, different modes of

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transportation in a competitive market, i.e. road, sea, air, and rail, have been used to provide better services. Due to the intense competition between these modes, a decrease in the service quality of the railway system can lead to a significant loss of its market share. In the meantime, it is noteworthy that the railway's system has played a special role sustainable development of the country due to its ability to transport a huge amount of shipment, better compatibility with the environment, less fuel consumption, and being economically justifiable for the transportation of domestic freight. Therefore, railway managers must expand therail network as a national objective, for which, it is necessary to have continuous, comprehensive, and coordinated planning in the area.

Railway planning is divided into three levels strategy planning, tactical planning, and operational planning according to the amount of investment, decision-making level, and time horizon. Because it is practically impossible to consider all three levels of planning in the form of a unique problem, usually different problems are investigated separately and sequentially. Consequently, strategy planning output is often used as the tactical planning input, and tactical planning output is used as the operational planning input[1].

The network design problem is one of the most important problems in strategic planning. In short, this problem deals with how to allocate alimited budget to the expansion of the railway network infrastructure, in such a way that certain objectives such as minimizing the shipping travel time, minimizing the expansion or maintaining cost, and maximizing the freight revenue, or maximizing the passenger revenue[2].

The present study seeks to find the optimal expansion of a railways network to entail the minimum cost while facilitating a certain level of input freight demand to pass through the network. We consider that the capacity of the underlying network is dedicated to freight transportation. Figure 1 depicts the scope of this research by considering various aspects of the problem.

After the introduction, section 2 briefly reviews the research background and the present study's position. Section 3 deals with the general statement of the problem. In section 4, the proposed greedy algorithm and the information required to implement this algorithm are described. In section 5, the railway network of Iran and the results of the algorithm implementation for this network are presented. Finally, the multiobjective approach for network expansion is introduced and the corresponding results are discussed. Conclusions and future research suggestions are given in section 6.

2. Literature review

This section introduces the concepts related to the research topic and reviews the literature on the network design problem. We end this section with a summary and a look at the position of the present study in the literature.

Rail transportation has many advantages due to its contribution to transporting bulk cargo on long routes, saving energy carriers, lower depreciation, high speed in unloading and loading, and last but not least, reducing environmental pollution[3]. Despite the mentioned advantages and with the increase in the demand for freight transport, during recent years, the share of rail freight transportation in Iran has not grown along with road transportation and has even decreased in some cases[4]. Increasing the share of rail transportation never be realized unless comprehensive studies are carried out in the field of freight transportation planning.

So far, various objective functions for the transportation network design problem have been proposed in the literature. For example, minimizing the average travel time, maximizing the revenue, minimizing air pollution or noise pollution, minimizing environmental costs, maximizing the demand attraction, and maximizing the sustainability of the network, among which, minimizing the average travel time is the most frequently applied [5-11].

The complexity of the problem of railway network design is partly due to the wide range of alternatives for expanding and increasing the capacity of the network, which has more variety compared to road transport. The solutions that are usually used to improve the freight transport capacity between railway axes are as follows:

1. Double tracking construction: increasing capacity through the construction of a new track [12]

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2. Blocking: dividing each track into several blocks to increase capacity[13]

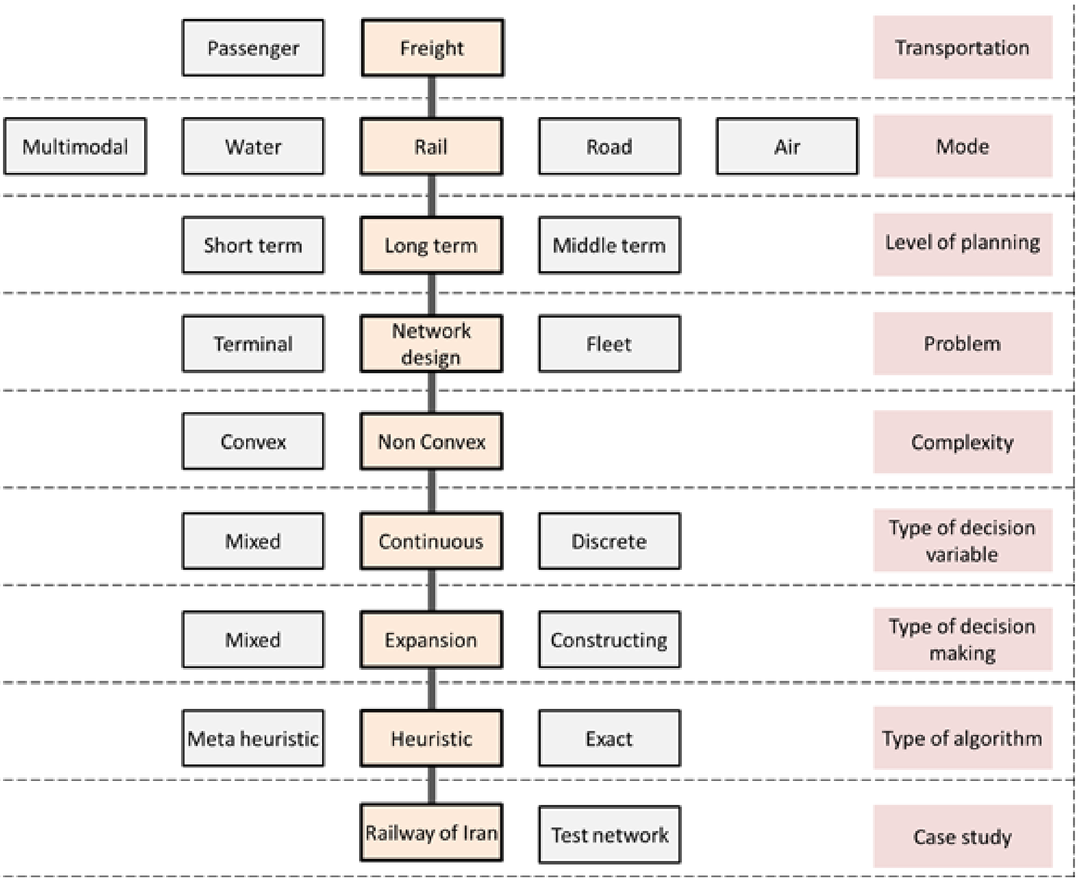

Figure 1. Scope of the present study

3. Electrification: increasing capacity by reducing train travel time using high-speed trains[14]

4. Classify shipment: Identify the classification plan for all shipments at all yards in the network [15],

5. Dispatching the long train: increasing the freight capacity by running the long train[16]

Given that there is only one choice of expansion for each block (i.e. two decisions: construction or do note alternative), and only 20 projects are considered for network expansion, the feasible space of the problem will contain 2^{20} combinatorial solutions and therefore achieving the exact solution even by powerful computers may take months[17]. By increasing the number of construction types from 2 to 6 (5+1 including do nothing alternative), the complexity of the problem increases from 2^n to 6^n solutions which makes the problem computationally intractable. That is why most of the studies conducted in the field of network design have focused on heuristic and meta-heuristic algorithms[18], and the studies addressing the exact network design solutions have remained rather limited[19].

Many factors are effective in choosing the mode and path of moving shipment. In the study of Kolian et al., based on the frequency of measures of effectiveness in previous studies, a list of measures was prepared including the cost of transportation, quality of transportation service, reliability of travel time, thedistance between origin and destination, speed, the flexibility of schedule, infrastructure availability, fleet availability, shipment characteristics, work experience of the company, and global package tracking. Although each of these factors can be importantat , the high level of decision-making, general measures of effectiveness are needed.

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The cost and travel time have been the priority of previous research, which is the basis of modeling in this research[20].

In the railway network design, the shortage of freight transport capacity in the network blocks has been widely discussed in the literature. According to previous research, the rail network's capacity bottlenecks and the lack of accessibility to important origin destinations will lead to a decrease in railways freight demand. Although the problem of bottlenecks has been studied before, the solutions presented for prioritizing network expansions have mostly been ignored[21].

The research of this paper is focused on the railway's network design to increase the capacity of the current lines. Therefore, we do not address the construction of new lines in the network and what is finally presented as the solution presents the percentages of expansions for network blocks. The ultimate decision of how to apply the expansions is left to upper-level railways policymakers. Given the research gap and the requirements defined by the railways of Iran, the main features of the current research can be presented as follows:

- Problem definition: Improving the performance of the rail network by focusing on the expansion of existing lines to meet the freight demand.
- Bi-level model: The objectives of the railway network design and routing problem are different; thus, this problem poses a bi-level modeling structure. Due to the non-convexity of this problem, it is very difficult to solve it by classical methods.
- Problem-solving method: A greedy heuristic algorithm is used to solve the proposed model.
- Case study: railway network of Iran is used as the case study to report the results.

3. Problem formulation

In this section, the mathematical background of railways network design is presented as a bi-level problem in two parts. In the first part, the problem of network design is stated in its general structure. In the second part, the traffic assignment problem, which is a sub-problem of the network design problem, is discussed.

3.1. Network design problem

The network design problem is usually formulated as a bi-level problem or a leader-follower problem. The upper-level problem is the problem of the leader/designer / decision-maker (i.e. government) who manages the transport network. An upper-level problem leads to an upper-level decision (to build or not to build a line) and includes a measurable objective (for example, minimizing total travel time), and constraints (for example, political, physical, and environmental constraints). In the upper-level problem, it is assumed that the leader can predict the behavior of the followers/users. The lower-level problem is the problem of finding the traveling path for followers/users on the network. The bi-level model allows the leader to incorporate users' reactions to decisions made to improve the network. This structure does not allow users to predict the leader's decision but only allows the users to determine their choice after knowing the leader's decision. Mathematically, the problem can be shown as follows [22]:

$$(U0) \quad \underset{u}{Min}\, F(u, v(u)) \tag{1}$$

$$s.t.$$

$$G\left(u, v(u)\right) \le 0 \tag{2}$$

where v(u) is obtained by solving the following model.

$$(L0) \quad \underset{v}{Min}\, f\,(u, v) \tag{3}$$

$$s.t.$$

$$g\left(u, v\right) \le 0 \tag{4}$$

F and u are the objective function and the decision variable vector of the high-level problem (U0), respectively. G is a function vector in the constraint of the upper-level problem, and f and v are the objective function and decision variables for the lower-level problem (L0), respectively. v(u) is called the response function of the users' reaction based on the flow pattern for the high-level decision u. Since v(u) is an implicit function that cannot be expressed explicitly, it is obtained by solving the L0 problem. The objective of the bi-level

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network design problem is to find the optimal decision vector u to optimize the objective function F according to the network design constraint (2) and the lower-level model with the objective function (3) and constraint (4).

Solving a bi-level network design problem using exact solution methods is very difficult because it is a non-convex problem. Ben-Ayed et al. (1988) studied bi-level problems and concluded that a bi-level problem, even with linear upper and lower-level problems, is NP-hard [23]. As a result, the application of approximate algorithms (e.g. heuristics) to tackle these problems is inevitable.

3.2. Traffic assignment problem

The traffic assignment problem is considered one of the most fundamental issues arising in transportation planning decision-making problems. The transportation managers are looking for the traffic flow to be able to evaluate the level of service for the network. The following objectives may be taken into account to formulate and predict the amounts of link traffic flows:

- Minimize the total travel time
- Minimize the distance traveled
- Minimize the fuel consumption
- Minimize the emission of pollutants

One of the main difficulties of traffic assignment corresponds to the prediction of users' choice behavior. Among the many efforts that have been made on traffic assignment models, the User Equilibrium (UE) concept can be distinguished as the most widely applied concept. The UE approach to the study of the supply–demand interactions assumes that the state of the real-world system can be represented by a set of path flows that is consistent with the corresponding path costs. Equilibrium path flows and costs are defined by a system of nonlinear equations obtained by combining the supply model with the demand model[24].

The UE definition often incorporates some simplifying assumptions. For example, it implies that users have full information about the underlying network (e.g. they know the travel time on every possible route). It also assumes that all individuals are identical in their behavior. The solution to the UE problem is based on the assumption that each user travels on a path that minimizes his/her travel time from origin to destination. As a result of this choice behavior, the travel times on all used paths connecting any given O-D pair will be equal and not greater than the travel times on any of the unused paths. Such a situation is called the UE in which no user can experience a lower travel time by unilaterally changing their routes[25].

The input of the traffic assignment problem includes network topology, capacity and travel time-volume function for each arc, and O-D pair demand. This problem has emerged as a powerful tool for analyzing large-scale urban transportation networks. The most frequently used algorithms for solving the traffic assignment problem can be listed as incremental traffic assignment method[25], convex combination algorithm[25], path-based algorithms[26, 27], and origin-based algorithms[28].

The travel time-volume functions are non-linear and asymmetric, which leads to the complexity of solving the traffic assignment problem. One of the most common travel time-volume functions used in road transportation planning is the "Bureau of Public Roads" (BPR) function which can be written as follows.

$$t_a(x_a) = t_a^0\left(1+\alpha\left({x_a}/{v_a}\right)^{\beta}\right) \quad (5)$$

where:

x_a : Traffic flow in link a,

v_a : Nominal capacity in link a,

t_a^0 : Free flow travel time (without traffic) in link a,

$t_a(x_a)$: Travel time-volume function in link a, and

α, β : Calibration parameters of travel time-volume function.

The travel time-volume function is widely used in road transportation studies, but its application in railways operations research has remained quite limited. Meanwhile, in the planning studies of rail transportation at the strategic level, a travel time-volume function for planning is required for capturing the

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realism of the problems and decision-making [29]. In this research, the study of the Isfahan University of Technology Research Institute is referred to model the travel time for Iran's railway network. Using various calibration scenarios, this study suggests the parameters α=4 and β=0.5 to model the link travel time of Iran's railway network [30].

4. The proposed greedy algorithm

To solve the network design problem based on minimizing the expansion cost, the proposed solution algorithm is presented. In this regard, we first take a look at the application of greedy algorithms in solving NP-Hard problems. Then the proposed greedy algorithm is presented. Finally, we discuss the complexity of the algorithm.

4.1. Introduction of the greedy algorithm

As stated in Section 3, the network design problem is classified as an NP-Hard problem in terms of computational complexity. To solve such problems, the solution methods are classified into two general categories: exact and approximate. Although the exact solution algorithms give the global solution through the feasible region, a modest increase in problem size might cause an explosion in computation time. Therefore, another group of algorithms called approximate algorithms was formed to solve these problems. The objective of the approximation algorithm is to come as close as possible to the global solution in polynomial time[31]. In general, the main idea in the approximate algorithm of NP-hard problems, such as the network design, is to make a trade-off between the quality and speed of the optimal solution. This means that the quality of the optimal solution is ignored to some extent, but, the running time to find the optimal solution is reduced.

Several algorithms have been proposed for the approximate solution of NP-Hard problems, including heuristic and meta-heuristic algorithms. Commonly, greedy algorithms are classified under heuristic algorithms. The reason why these algorithms are named greedy is that the solutions are based on greedy ideas that are hidden in the structure of the algorithm. This means that the algorithm picks the best solution at the moment without regard for consequences. It picks the best immediate output but does not consider the big picture, hence it is considered greedy[32, 33].

The proposed algorithm to solve the network design problem in this article is a greedy algorithm that tries to reduce network expansion costs as much as possible. The steps of this algorithm are shown in Figure 2. In the following, the components of this algorithm are reviewed in more detail.

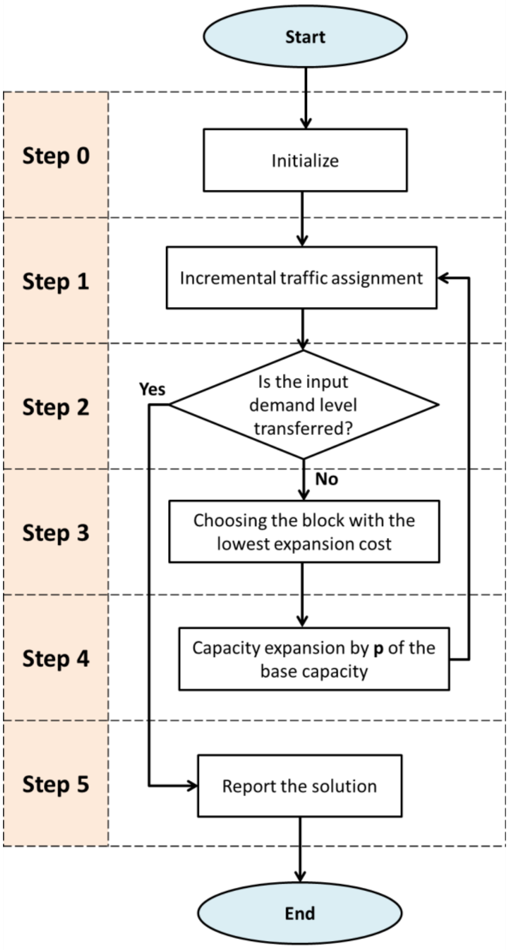

Figure 2. The flowchart of the proposed greedy algorithm

Step 0: Initialize

In this step, the algorithm is given the necessary and desired inputs. This information includes the travel demand matrix between O-D pairs, the number, and names of network stations, the characteristics of network blocks (length, capacity, and whether single or double track), the percentage of partial expansion of the network (p), the accuracy of incremental traffic assignment, and unit cost of expansion of each block.

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Step 1: Incremental traffic assignment

In this step, the algorithm calculates the equilibrium flow using the incremental traffic assignment method. At the end of this step, one of these two situations may happen: (1) the whole demand is allocated to the network, or (2) a part of the demand is allocated to the network, and the rest demand is not sent due to overcapacity blocks. As a result, the algorithm eventually encounters a set of overcapacity blocks whose flow has exceeded the corresponding nominal capacity.

Step 2: Termination condition

If the whole demand has been transported, there is no need to expand the network and the algorithm ends. Otherwise, one block must choose from among the blocks that have reached their capacity.

Step 3: Greedy rule

In this step, the algorithm faces several candidates, i.e. overcapacity blocks. In a greedy approach, the algorithm selects the block with the lowest expansion cost among candidates.

Step 4: Network Expansion

The block selected in step 3 increases the corresponding capacity by the value of p in percentage. By choosing a small enough value for p, it is possible to assure that using the added capacity.

Step 5: Report the optimal solution

The solution obtained is reported

4.2. Computational complexity of the algorithm

According to the loop 1-2-3-4-1 in Figure 2, the algorithm faces four computational operations in each iteration, which are: (1) traffic assignment, (2) termination condition, (3) greedy selection of an overcapacity block, and (4) partial expansion of the selected block. Among these steps, the traffic assignment part is the part that imposes the main computational burden on the algorithm.

Due to the lack of information about expansion costs for railways blocks over the topography of Iran's network, for simplicity, we assume in this paper that the expansion cost for each block has proportionate to the block length.

5. Analysis of the results

This section examines and analyzes the performance of the proposed algorithm. In the first part, we introduce the railway network of Iran, which is used as a case study in this research. In the second part, we discuss the concept of multiobjective function involving two or more optimization conflicting objectives. In the third part, the results of the proposed greedy algorithm for Iran's network are presented and the analysis related to the multiobjective approach is presented.

5.1. The railway network in Iran

In 2022, Iran has more than 14,000 kilometers of railways network and 434 stations (technically consisting of classification stations, overtaking stations, maintenance stations, and industrial stations)[34]. The general scheme of Iran's railway network is depicted in Figure 3. It must be noted, however, that the most up-to-date network information and demand matrix applied in our research dates back to 2018. More up-to-date analyses will call for a revision in the input data based on the changes in recent years.

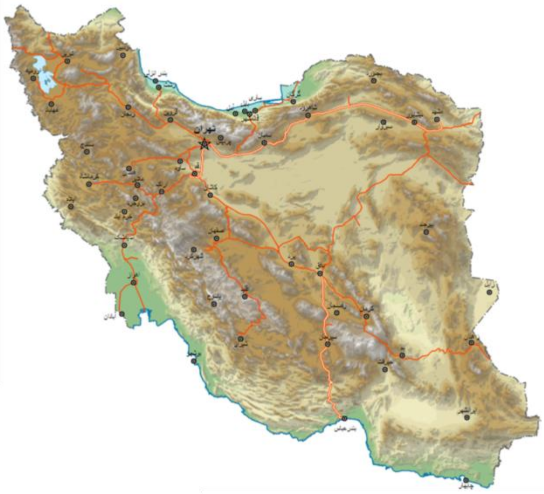

Figure 3. Scheme of the railway of Iran

5.2. Pseudo-Pareto solution for multiobjective optimization

In the course of the iterations, the proposed algorithm generates a track of solutions that can be analyzed based on their two criteria (objective functions) namely (1) network throughput and (2) expansion costs. Depending on which objective function to prioritize, the optimal solution to the problem can change. In other words, the track of solutions offers a

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trade-off between the two mentioned objectives. As a result of that, these solutions can stand for “Pareto” optimal solutions. Though regarding that, there is no guarantee for the global optimality of the solutions, we will use the term “pseudo-Pareto” solutions for these solutions.

To deal with these solutions in a multiobjective framework, we applied a weighted sum method that combines all the objective functions into a single scalar objective function[35]. This is accomplished by multiplying each of our objectives by pre-defined weights. The weight given to an objective is normally assigned to be proportional to the objective’s relative importance in our problem. To take care of the magnitude of our objective functions, we also apply a normalization process[36] in which both objectives are dimensionless and scaled-down between 0 and 1.

The objectives or criteria in the solutions can be summarized in the following two: measures maximization of demand value D and minimization of expansion cost C. These two measures are combined into a single objective function by multiplying each measure by a predefined weight, as follows:

$$\begin{aligned} Z &= w_D D^N + w_C C^N \\ &= w_D \frac{D - D_{min}}{D_{max} - D_{min}} + w_C \frac{C_{max} - C}{C_{max} - C_{min}} \end{aligned} \tag{6}$$

Where:

D_{min}: the lowest value of demand among the set of obtained solutions (million tons),

D_{max}: the highest value of demand among the set of obtained solutions (million tons),

C_{min}: the lowest amount of network expansion cost among the set of obtained solutions (kilometers),

C_{max}: the highest amount of network expansion cost among the set of obtained solutions (kilometers),

w_D: the multi-objective weight accounting for the network throughput, and

w_C: the multi-objective weight accounting for network expansion costs.

As a result of this weighting and normalization system, each of the objective functions is normalized as a number between [0, 1], and as the value of the normalized objective function, approaches 1, the quality of the solution increases.

5.3. Result

The proposed algorithm of this study is implemented in the Java programming language. Computational experiments are conducted on a desktop computer with a Core(TM) i5-4200U CPU@1.60 GHz CPU and 8.0 GB of RAM. The amount of expansion for the selected blocks in step 4 of the algorithm is considered to be 20%. In other words, in each iteration of the algorithm, the capacity of the selected block is increased by 20% of the block’s basic capacity. To obtain the results, the algorithm performed 490 iterations only in a 1746 seconds run-time, which supports the light computational burden and fast performance for the proposed greedy algorithm.

Having the algorithm implemented and run, the amount of network expansion is reported for different amounts of demand which are considered from 42 million tons annually and increased to the demand of the planning horizon which equals to 70 million tons annually.

We initially reported the amount of block expansion to transfer the total travel demand of 70 million tons. The demand information used in this study is taken from and referred to the study of Seyedvakili et al. [37]. However, unlike the study of Seyedvakili et al.[37], the travel time is not constant and the travel time-volume function, as discussed earlier, is used to estimate the travel time in blocks. We apply the travel time-volume function proposed in a previous study on Iran’s railway network performed by the Isfahan University of Technology[1][38].

Considering the huge number of blocks in the Railway of Iran, it is not possible to report the detailed amounts of expansions for all network blocks. Therefore, the percentage of expansions of blocks is summed up for the 19 regions of Iran's network and depicted in Figure 4.

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[1] It is worthy to note that the value of 70 million tons of freight per year has been proposed as a moderate level of freight transportation demand to be fulfilled by adopting long-term strategies in the study of Isfahan University of Technology[38]. However, this number can be altered to higher/lower levels as an input to the model in this paper.

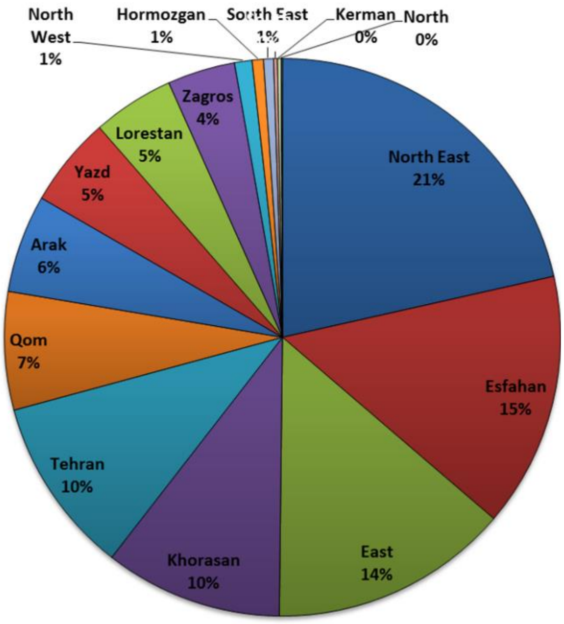

Figure 4. Total percentages of capacity expansions required for 70 million tons per year over 19 regions of Iran's railway network

Figure 4 shows that the highest level of a network expansion to fulfill the freight shipment of 70 million tons per year is associated with the North East region. This area of Iran's network consists of two parts. The first part includes the distance between Garmsar (Tehran area) and Niqab (Khorasan area) stations. There is a total of 926 kilometers of railways network constructed in this area, of which 58% (i.e. 540 kilometers) consists of double-tracked railways. The second section starts at Golugah station and ends at Incheh Boroun station. This area has 151 kilometers and a total of 8 freight and passenger stations[34]. This area also plays a significant role in railways freight transportation due to its location between the east and northeast of Iran's network. For other areas, the number of expansions can also be observed in Figure 4.

From the results obtained from the algorithm, it is interesting to see how network expansions should be prioritized in the planning horizon. In other words, should projects first be built in the eastern area or the Zagros area? Answering this question would be beneficial to apply a multi-period expansion scheme in the planning horizon. For this purpose, the arrangement of expanded blocks has been extracted in order of appearance in the course of the iterations of the algorithm. We observed that to reach the total demand of 70 million tons per year, the algorithm proceeds through 490 iterations. We divided the iterations into two parts. The expansion of blocks with higher priority occurs in iterations 1 to 250 and then iterations 251 to 490 correspond to the blocks with the next level of priority to be expanded.

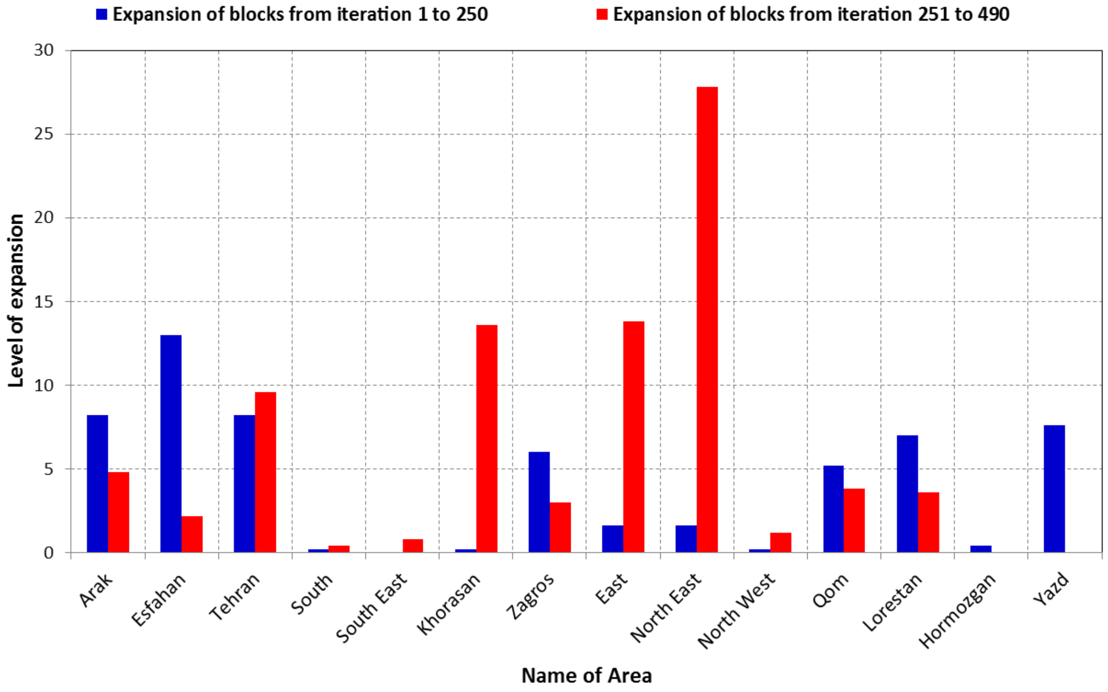

Figure 5. Ordering the expansion of blocks in terms of areas

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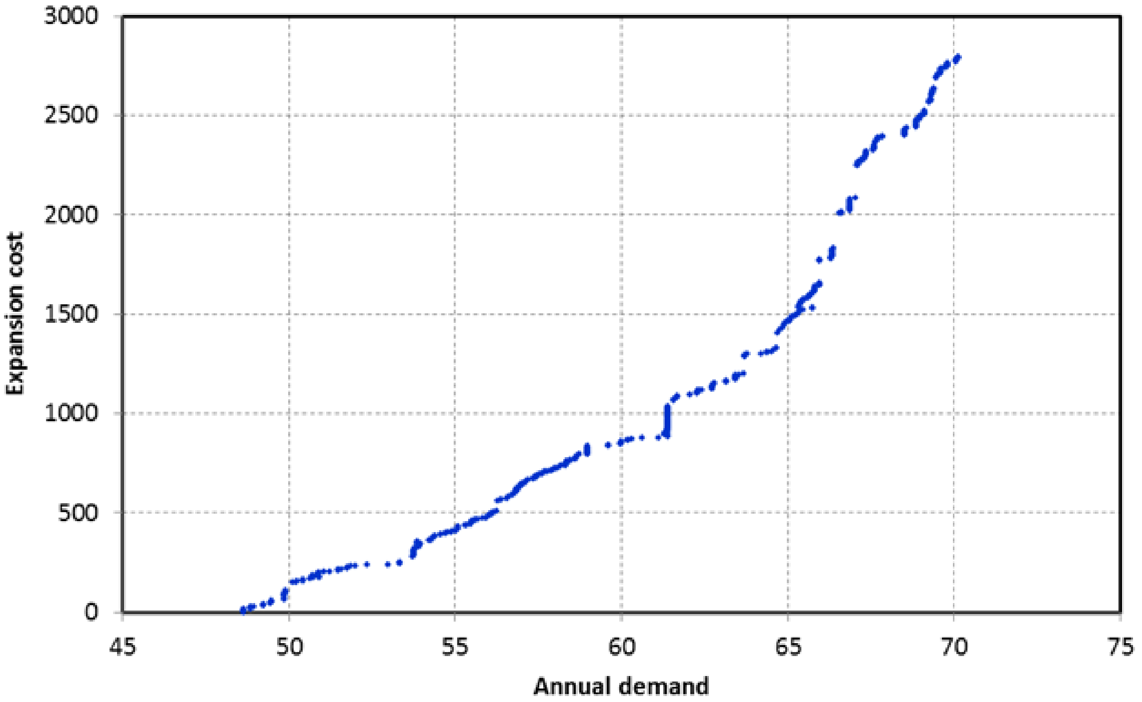

Figure 6. showing the concept of two objectives in the results of the proposed algorithm

Figure 5 shows that for the areas of Arak, Isfahan, Zagros, Qom, Yazd, and Lorestan, more expansion is suggested in the earlier iterations of the algorithm, offering a higher priority of expansion for these areas (shown in blue color). However, this trend interestingly changes as the algorithm gets to iterations 251-490. In these iterations, the North-East, East, Khorasan, and Tehran regions are ahead of other areas in the expansion (shown in red color).

We also examine the behavior of the proposed algorithm in obtaining pseudo-Pareto solutions based on the two measures of (1) network throughput and (2) total expansion costs, as discussed earlier. In Figure 6 the horizontal axis stands for the network throughput and the vertical axis shows the required total expansion costs. As expected, the amount of total expansion costs required for the network increases with higher amounts of network throughput. This trend which is shown in Figure 6 can be helpful to provide insight for decision-making and used to further perform further benefit-cost analyses.

As stated in section 5.2, one of the advantages of having Pareto optimal solutions is to find the best solution by weighing different objectives. As an example, here, we apply the weighting system of w_D =0.6 and w_C = 0.4 which implies that 60% and 40% of the importance in the weighted objective function is put over the network throughput and total expansion costs, respectively. It must be noted that these weights are used only for illustrative purposes, and in real-world applications can be determined by upper-level decision-makers. Multi-attribute decision-making methods such as Analytic Hierarchy Process (AHP) can also be applied in this regard.

To analyze the pseudo-Pareto solutions extracted by the proposed algorithm, the importance of the network throughput (in percentages) is taken into account as an input and the value of total block expansions in the network is reported. To clarify the concept of total block expansions in the network, suppose that three blocks in the network need to be expanded by 60%, 30%, and 20%. Then, the mentioned measure would add up to 0.2+0.3+0.6=1.1. Given that, figure 7 shows the results of the algorithm for increasing the importance of demand against the importance of block expansion obtained by the greedy algorithm. As this figure suggests, as long as the importance of the network throughput is less than 20%, the algorithm does not lead to

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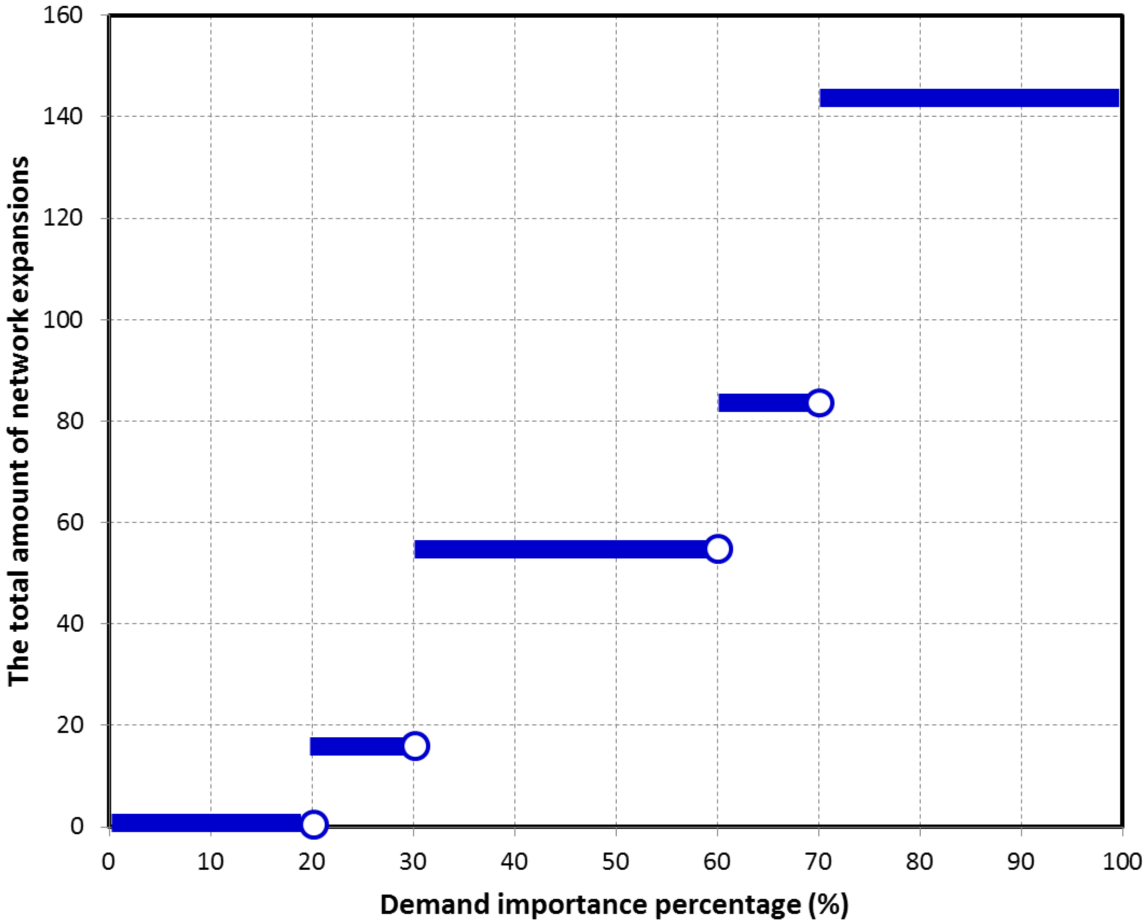

Figure 7. The total amount of network expansions with regard to the weight of network throughput in the objective function

any expansion in the network, and this is due to the high importance (weight) put over the total expansion costs of the network. When the importance of the throughput exceeds 20%, the algorithm seeks to facilitate more input demand through the network by adopting further expansions. It can be observed that, up to the weight of 30% for network throughput, there is no change in network expansion costs. As the importance of the throughput reaches values greater than 30%, block expansions notably increase. The greatest amounts of network expansion appear as the weight put over the network throughput goes beyond 70%.

6. Conclusion

The current research was dedicated to the problem of expanding the railway's network to minimize the expansion costs while facilitating the transportation of an input freight demand. To this end, we proposed a greedy algorithm that iteratively selects and expands overcapacity blocks of the network that incur the least expansion costs to the network. The results of implementing the algorithm over Iran's railway network can be summarized as follows:

1. The proposed greedy algorithm reveals a light computational effort and fast performance. In the case of Iran's railway network, it is capable to achieve the 490 pseudo-Pareto solutions in less than a 1-hour run-time.

2. The algorithm was implemented and tested to facilitate the transportation of 70 million tons of freight demand. The results of network expansion show that the North East region of Iran's network gains the highest expansion values.

3. The record of the solutions generated in the course of the algorithm also shows that, in a multi-period scheme in the planning horizon,

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expansions over Arak, Isfahan, Zagros, Qom, Yazd, and Lorestan receive the highest levels of priority.

4. The pseudo-Pareto solutions of the algorithm were evaluated by applying different weights for the network throughput. The results show that increasing the network throughput weight to more than 70% leads to a network throughput of 70 million tons in the solutions. Also, by reducing the importance of the network throughput to less than 20%, the algorithm offers solutions with zero expansion costs (“do nothing” alternative in decision-making).

The findings of this research can be extended as follows:

1. To solve the traffic assignment problem, this study applied the travel time-volume function proposed by Esfahan study for the railway of Iran. However, the use of more advanced functions such as the study of Hwang and Ouyang[39] may be considered in future research.

2. In this research, the unit cost of expansion of each block was considered proportionate to the length of that block. It is clear that in reality, this cost is highly dependent on various factors, including the geographical conditions of the route, as well as the land acquisition costs. Incorporating such details is an important direction to be considered in the future.

3. The interaction between freight and passenger trains within the limited capacity of the underlying network poses modeling challenges. For modeling simplicity, such interaction was not addressed in this paper and can be an interesting topic for future research.

4. A greedy heuristic algorithm was introduced and applied in our research. However, many novel meta-heuristic algorithms have been proposed in the literature to tackle network design problems. Application of these algorithms and comparing their performance with the algorithm in this study can also be an interesting topic.

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