A Comprehensive Approach for Railway Crew Scheduling Problem (Case Study: Iranian Railway Network)

Amin Khosravi[1], Mohammad Tamannaei [2], Mohammad Reisi-Nafchi [3],

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Abstract
The aim of this study is to propose a comprehensive approach for handling the crew scheduling problem in the railway systems. In this approach, the information of different railway trips are considered as input and the problem is divided to three separated phases. In phase I, we generate all feasible sequences of the trips, which are named as the pairings. A depth-first search algorithm is developed to implement this phase. In phase II, the pairings constituting the optimal solution are to be obtained. Both mentioned phases are handled in a centralized decision-making system for the entire railway network. Phase III aims to locally assign the crew groups to the optimal pairings. To solve the problem in phase III, a new mathematical model is developed in this paper. The model can determine the minimum required crew groups, and optimally assign the crew groups to the selected pairings of each home depot. In order to evaluate the developed algorithm and model, the Iranian railway network is evaluated by consideration of all passenger trips of the network. The results show that the proposed approach is capable of efficiently generating the optimal schedules for the railway crew groups in a reasonable computation time.

Keywords: Railway, crew scheduling, trip, pairing, optimal solution

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Correspondions author E-mail: m.tamannaei@cc.iut.ac.ir

1. MSc. Student, Department of Transportation Engineering, Isfahan University of Technology, Isfahan, Iran

2. Assistant Professor, Department of Transportation Engineering, Isfahan University of Technology, Isfahan, Iran

3. Assistant Professor, Department of Industrial and Systems Engineering, Isfahan University of Technology, Isfahan, Iran

1. Introduction

The crew scheduling is considered as one of the most important aspects of the railway transportation planning. The crew scheduling problem (CSP) in railway system is the assignment of the crew groups to the pre-determined train trips. A sequence of the two or more trips is named a 'pairing'. The optimal crew schedule consists of the crew plans, for which, the cost of assigning the crew groups to the pairings is minimized. The total crew cost includes different types of cost, such as the employment cost, the variable cost for handling the specific trips, the transition cost for crew transfer from home depots to the other depots, and etc. these costs can cover a main part of the transportation system cost. A small improvement in crew scheduling plans may lead to great saving in annual costs of the system. Hence, the crew scheduling problem is currently an active research area for the railway systems. In the present research, we investigate the constraints of the railway crew planning and scheduling, along with the models and the methods used to solve different phases of this issue. Also, a comprehensive approach including all phases of the railway crew scheduling problem is proposed, based on the Iranian railway rules.

The current article is organized as follows: In Section 2, a review of the literature associated to the railway crew scheduling problem is presented. The proposed comprehensive approach is completely elucidated in section 3. In the third phase of this approach, a new mathematical model is developed, as the contribution of the paper. In section 4, the proposed approach is applied for Iranian railway network. Finally, the concluding remarks are given at the end to summarize the results of this article.

2. Literature Review

In the railway industry, crew scheduling have received much attention. Caprara et al. studied the crew scheduling problem in Italian railways, aimed to minimize the operational costs and number of required staffs. The mathematical model was based on set covering problem, solved by the Lagrangian relaxation method [Caprara et al. 1999]. In another paper by Caprara et al. the assignment of the crew groups to the pairings is considered. This type of problem is said to be the crew rostering problem [Caprara et al. 1998]. Ernest et al. considered operating crew management arising from a real application in National Rail Australia. In this rail network, the freight train timetable is repeated weekly, rather than daily as in the European network. Based on such an argument, the authors did not apply the methods for train crew scheduling developed for European railway systems [Ernest et al., 2001]. Sepehri and Fathaliha proposed a mathematical model for railway CSP based on the graph theory. The study is performed by regarding the constraints and the rules associated to Iranian rail network [Sepehri and Fathaliha, 2001]. Pourseyedaghai and Salehi discussed the train conductor scheduling in railway network, according to the periodic need of railway as a result of periodic train scheduling. In this study, a heuristic algorithm is used to generate the feasible pairings, aimed to minimize the required crew groups [Pourseyedaghai and Salehi, 2006]. Kroon et al. considered three main objectives for railway CSP in Netherland: minimization of pairing costs, fairness in crew workloads and prohibiting the delay propagation. To solve the problem, a column generation solution method is proposed [Kroon et al., 2008]. Guillermo and José presented a combination algorithm for CSP, by using the Tabu search metaheuristic method. To evaluate the algorithm, Chile railways were examined [Guillermo and José, 2009]. Yaghini and Fathipour considered railway CSP based on column generation approach, aimed at minimization of costs and travel times [Yaghini and Fathipour, 2009]. In a study conducted by Yaghini et al. the optimal pairings of the railway CSP are determined, by using a model based on minimum-cost flow formulation. It was concluded in this paper that the proposed model can reduce the computation time required to solve the problem [Yaghini et al. 2009]. Yaghini and Ghanadpour solved railway crew scheduling problem using a heuristic two-phase model. This model, was concerned with building the work schedules of crews needed to cover a planned timetable [Yaghini and Ghanadpour, 2010]. Kwan investigate the railway CSP for British network. He used set covering model to select the optimal pairings [Kwan, 2012]. Jut and tanman presented a branch-and-price solution method to model CSP, aimed to solve the problem for the entire European railways in a short computation time. In this paper, the railways are divided into several sun-regions, for each of which, the feasible pairings are generated in order to cover the specific trips [Jut and tanman, 2012]. Shijun and Yindong solved the railway CSP by using a set covering model. They also developed an exact solution method based on column generation [Shijun and Yindong, 2013]. Shijun et al. (2013) studied CSP for Chinese railways, aimed to reduce the number of work shifts, considering the break times of the crew groups. The work shift was defined as a continuous period of time during which a driver is working [Shijun et al. 2013]. Hanafi and Kozan presented a mathematical model to exactly solve the crew scheduling problem. They also developed a heuristic approach based on simulated annealing solution method to find near-optimal solutions in a reasonable time [Hanafi and Kozan, 2014]. Farhadfar et al. developed a model based on traveling salesman problem, aimed to minimize the cost of pairing selection. They also presented a Tabu search heuristic solution method to solve the problem [Farhadfar et al. 2015]. In table 1, a summary of some previous studies for solving the railway crew scheduling problem is presented.

According to our literature review for the railway crew scheduling problem, different models are developed based on the rules and specific conditions of the railway systems around the world. It is also understood that most of the past studies have considered one of the phases of the railway crew scheduling problem. To our knowledge, few attentions are reported to consider more than one phase of the railway crew scheduling problem.

The aim of our study is to propose a comprehensive approach for handling the rail crew scheduling problem, based on local conditions of Iranian rail network. The other contributions of this Paper are as follows:

-Development of a mathematical model for assignment of crew groups to the pairings.

-Determination of the best time horizon for work shift lengths.

3. The Comprehensive Approach

In the railway systems, the crew management is performed based on the train timetable. In this timetable, information and some specifications of the trips are presented. Each trip has five specifications, which are considered as input parameters of the crew scheduling problem: home depot, destination depot, trip starting time, trip ending time and hour value (cost) of the trip.

As mentioned above, a pairing is a sequence of the two or more trips. A pairing, in which it is possible to generating a logical sequence of the trips according to the time and place considerations, is designated as a ‘feasible pairing’. Among feasible pairings, ones that cover all the trips in a minimal total cost are constitutive components of the system optimal solution. The railway crew scheduling problem can be partitioned to three phases. These phases are:

-Phase 1: Generating all feasible pairings.

-Phase 2: Finding optimal pairings which are included in the optimal solution.

-Phase 3: Assigning the crew groups to the optimal pairings.

The solution approach is different in the above phases. In the phase 1 and 2, a centralized approach is applied, i.e. all the trips of the trains timetable in the railway network are considered. But the third phase approach is local and it is applied for each depot individually. In Figure 1, the difference of the solution approaches is shown in the mentioned triple phases of the railway crew scheduling problem. Characteristics of each applied phases in the current research are described in the following subsections.

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Table 1. A summary of some previous studies in railway crew scheduling problem

Authors (Year)	Objectives: Finding optimal pairings	Objectives: Assigning crew groups to	Objectives: Fairness in crew workload	Specific notes applied in the research
Caprara et al. (1998)	✗	✓	✓	----------
Ernest et al. (2001)	✓	✓	✓	Development of cyclic work lines in railways
Sepehri, Fathaliha (2001)	✓	✗	✗	No solution method is presented
Sepehri et al. (2004)	✗	✓	✗	----------
Pourseyedaghai et al. (2006)	✓	✓	✓	Periodic train conductor scheduling
Yaghini et al. (2009)	✓	✗	✗	Based on minimum-cost flow model
Guillermo and José (2009)	✓	✗	✗	Development of Tabu search method
Yaghini, Fathipour (2009)	✓	✗	✓	Development of a column generation method
Jütte, Thonemann (2012)	✓	✗	✗	Development of branch-and-price method
Shijun et al. (2013)	✓	✗	✗	Special constraints on rest time durations
Shijun and Yindong (2013)	✓	✗	✗	Development of a column generation method
Hanafi, Kozan (2014)	✓	✗	✗	Consideration of special cases for pairing times
Farhadfar et al. (2015)	✓	✗	✗	Model based on traveling salesman problem

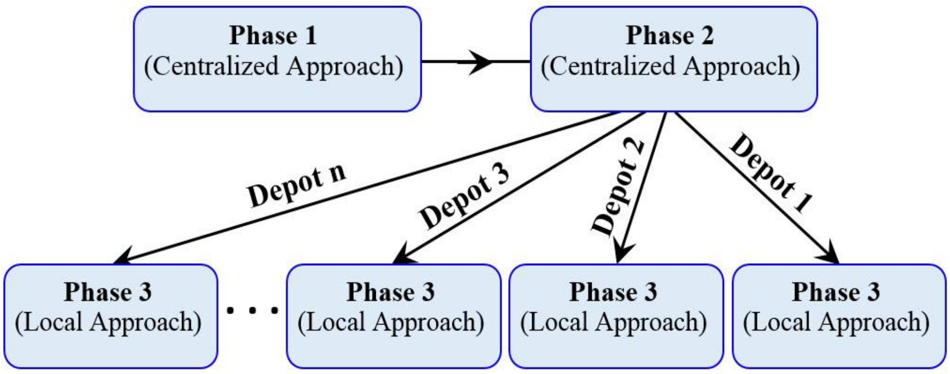

Figure 1. Difference of the solution approaches in the triple phases of the problem

3.1 Phase 1: Generating all Feasible Pairings

In the first phase of the railway crew scheduling problem, all feasible pairings are generated. In the current research, a 'feasible pairing' is defined as a sequence of two or more trips which have the following specifications:

a) Home depot of the first trip and destination depot of the last trip must be the same.

b) For each two consecutive trips, the destination depot of the first trip and the Home Depot of the second one must be the same.

c) For each two consecutive trips, the starting time of the second trip must be greater than the sum of the ending time of the first trip and minimum gap time between these two trips.

d) Time interval between the starting time of the first trip and the ending time of the last trip must be lower than the maximum allowed elapsed time of each pairing. To generate feasible pairings, in this study an algorithm was designed based on the depth-first search (DFS) strategy.

In this algorithm, all feasible sequences of the trips are considered and sequences which have the above four specifications are designated as feasible pairings. In Figure 2, the flowchart of this algorithm is drawn.

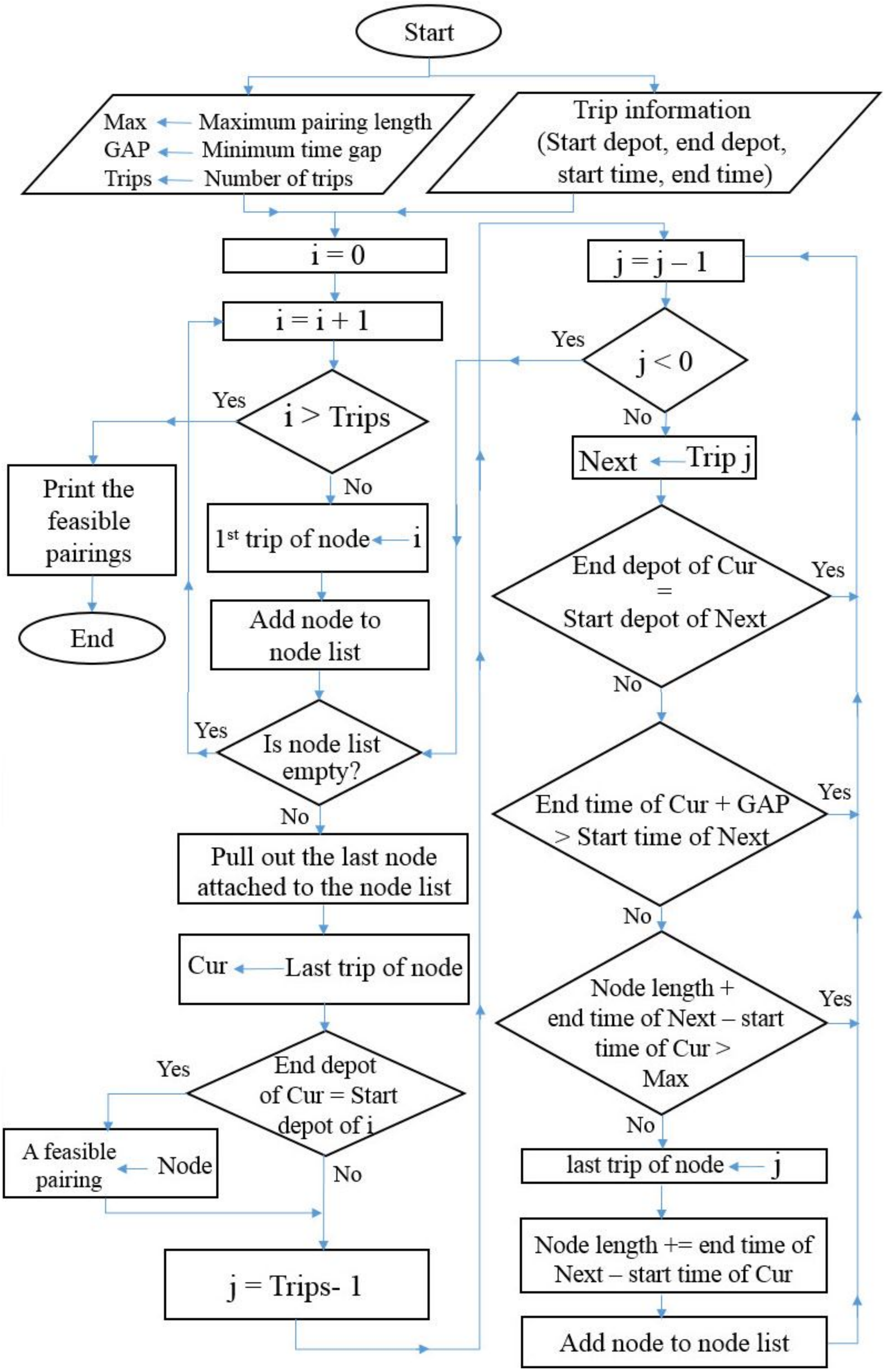

Figure 2. Flowchart of the proposed algorithm for the first phase: generating all feasible pairings

3.2 Phase 2: Finding the Optimal Pairings

In the second phase of the railway crew scheduling, optimal pairings are found among all feasible pairings which were generated in the first phase. In this study, a set covering model was applied to find optimal pairings. This model was used in the last similar researches too. In this model, FP is the set of feasible pairings and j is an index which is related to a feasible pairing ($j \in FP$). In addition, T is the set of all trips and t is an index which is related to a trip ($t \in T$). The mathematical model is as follows:

$$Min \sum_{j \in FP} C_j x_j \tag{1}$$

$$s.t. \sum_{j \in FP} a_{jt} x_j \geq 1 \qquad \forall t \in T \tag{2}$$

In this model, C_j is the relative cost of performing jth pairing. Binary parameter a_{jt} is the output of the first phase of the crew scheduling problem and specifies existing or not existing of the tth trip in the jth pairing. Binary variable of the model (x_j) represents the decision about selecting the jth pairing as one of the optimal pairing in the optimal solution. The objective function of the model (Equation 1, is minimizing the total cost of performing the selected pairings. Constraint (2) guaranties the existence of each trip in at least one of the selected pairings in the optimal solution. The output of the second phase represents the optimal pairings, which are included in the optimal solution. Each of these pairings is assigned to the home depot of the first pairing trip. So, each depot manages some of the optimal pairings.

3.3 Phase 3: Assigning the Crew Groups to the Optimal Pairings

The third phase is performed in a local level and for each individual depot. In this phase, the crew groups of each depot are assigned to the pairings which were designated to start in this depot in a previous phase. Assignment procedure must be done at a minimal total cost. Total cost includes crew employment costs and costs of performing the pairings by the crew groups. The required notations to present the third phase model are defined in Table 2.

Table 2. Notation of the third phase mathematical model

Notation		Description
Sets	P	Pairings set of the depot
	C	Crew groups set of the depot
Parameters	NP	Number of pairings
	Dur_p	Time duration of the pairing p
	$Rest_p$	Rest time after finishing the pairing p
	ST_p	Starting time of the pairing p
	ET_p	Ending time of the pairing p
	RT_p	Ending time of the rest time of the pairing p
	T_{Max}	Maximum allowed time for driving in a working shift
	T_{Min}	Minimum required time for driving in a working shift
	C_p^c	Assignment cost of the crew group c to the pairing p
	C_c	Fixed cost of employment of the crew group c
	M	A large positive integer number
Decision variables	x_p^c	(Binary) If the crew group c is assigned to the pairing p, it is equal to 1; otherwise
	y_c	(Binary) If the crew group c is employed, it is equal to 1; otherwise 0.

The proposed mathematical model of the third phase is as follows:

$$Min \quad \sum_{c\in C}\sum_{p\in P} C_p^c\, x_p^c + \sum_{c\in C} C_c\, y_c \tag{3}$$

s.t.

$$\sum_{c\in C} x_p^c = 1 \qquad \forall p\in P \tag{4}$$

$$\sum_{c} y_c \le NP \tag{5}$$

$$\sum_{p\in P} x_p^c \le NP.y_c \qquad \forall c\in C \tag{6}$$

$$\sum_{p\in P} x_p^c Dur_p \ge T_{Min}\, y_c \quad \forall c\in C \tag{7}$$

$$\sum_{p\in P} x_p^c Dur_p \le T_{Max}\, y_c \quad \forall c\in C \tag{8}$$

$$x_p^c + x_{p*}^c \le y_c \quad \forall c\in C, \forall(p,p^*) \mid (ST_{p*} \le ST_p < ET_{p*} + Rest_{p*}) \tag{9}$$

$$x_p^c \in \{0,1\} \qquad \forall c\in C,\ \forall p\in P \tag{10}$$

$$y_c \in \{0,1\} \qquad \forall c\in C \tag{11}$$

To solve the third phase of the railway crew scheduling problem, a mathematical model is suggested in this research. Along with assigning the crew groups to the pairings, this model specifies the required number of crew groups to perform the pairings of each depot. Output of the model is an optimal solution of the problem, i.e. final value of the decision variables are the best ones to achieve the best value of the objective function (total cost).

The above model objective function attempts to minimize the total cost. The objective function, which is presented in Equation (3), includes two parts: assignment cost of the crew groups to the pairings and fixed of the employment of the crew groups. The descriptions of the constraints are as follows:

-Covering all of the pairings: Constraint (4) forces each pairing to be assigned exactly to one crew group such that all pairing are covered.

-Maximum number of employed crew groups: Constraint (5) represents that the total employed crew groups cannot be greater than the number of pairings.

-Relation between decision variable: By constraint (6) if the crew group c is not employed ($y_c = 0$) then this group must not assigned to any pairings; otherwise ($y_c = 1$), it can be assigned to at most *NP* pairings.

-Minimum and maximum time in a working shift: Minimum and maximum allowed time for driving in a working shift are handled by Constraint (7) and (8) respectively.

-Prevention from assigning the overlapping pairings to one crew group: In some railway systems, such as Iranian railway, each two pairings can be assigned to one crew group if there will be considered at least a pre-specified rest time between the ending time of the first pairing and the starting of the second one. Most times, the duration of the rest time is considered to be not lower than the first pairing time duration. In other words, if two certain pairings have an overlap they cannot be assigned to one crew group. In this case, the overlap concept is not limited to the time duration of two pairings but it is applied for existing an overlap in the sum of elapsed time of a pairing and its following rest time (which is sometimes equal to the elapsed time of a pairing). In Figure 3, all possible cases of pairing p and p^* are shown graphically.

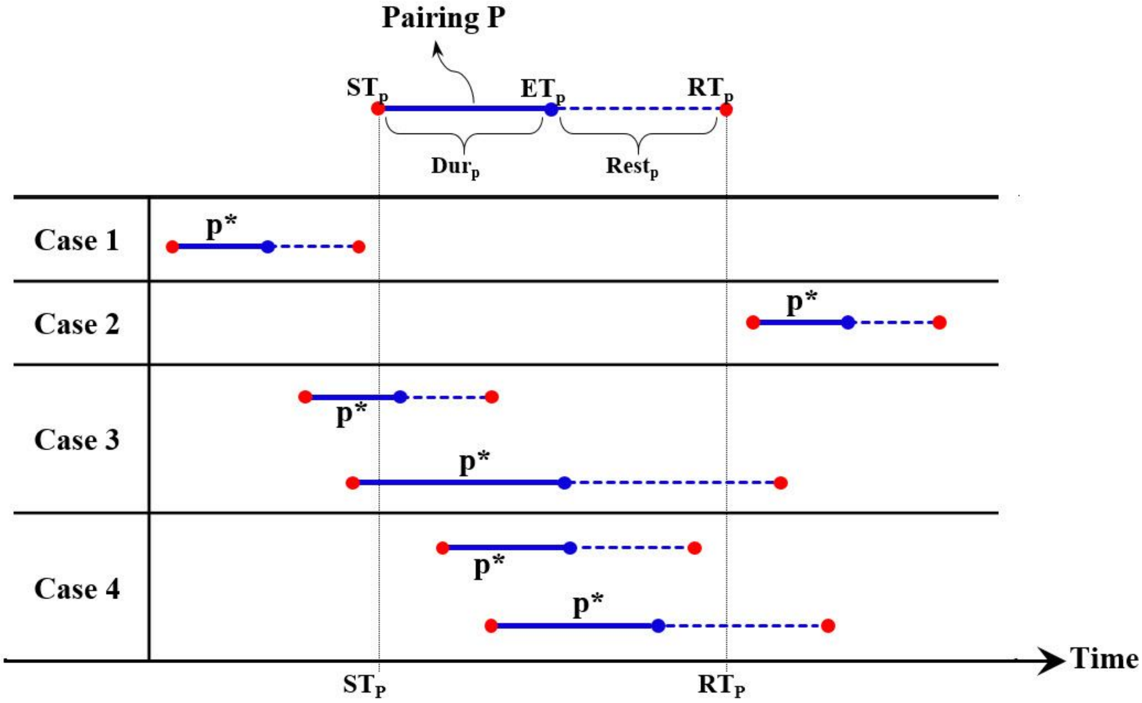

Figure 3. Possible cases of pairing p and p^*

The mentioned cases are:

Case 1: The end of rest time of the pairing p^* is lower than the start time of the pairing p.

Case 2: The start time of the pairing p^* is lower than the end of rest time of the pairing p.

Case 3: The start time of the pairing p is between the start time of the pairing p^* and the end of rest time of the pairing p^*.

Case 4: The start time of the pairing p^* is between the start time of the pairing p and the end of rest time of the pairing p.

The cases 1 and 2 are acceptable for the two pairing. But, cases 3 and 4 are not acceptable because of overlapping. Constraint (9) is imposed for each pair of pairings which has similar condition to the cases 3 and 4. This constraint represents that these pairs of pairings must not be assigned to one crew group.

Constraint (10) and (11) determine the type of decision variables of the model.

The first phase algorithm, the second phase mathematical model and the proposed model of the third phase were coded in the JAVA programming language. To solve the models in the last two phases, the CPLEX12 solver was used.

4. Case Study: Railway Network of The Islamic Republic of Iran

In this research, to evaluate the proposed approach performance the railways network of Islamic Republic of Iran is investigated. Iranian railway network has 18 regions and 27 depots as passenger stations such that the passenger trips of the network are started from these depots. In Figure 4, the 27 depots of this network are shown.

To evaluate the proposed triple phase approach, information of all scheduled passenger trips of Iran was obtained from Islamic Republic of Iran Railway Association. This information is about all passenger trips of 18 regions. Some samples of this information are presented in Table 3.
Currently, crew scheduling for passenger trips is performed manually in Iran, and based on the experiences of experts. A schedule, which is sent by Islamic Republic of Iran Railway

Association to each depot, is prepared according to the following considerations:

1. Assigned pairings to the crews of one depot are usually continued to the border of its region. Hence, long pairings are divided to some shorter ones.
2. The number of each depot crews is considered as the most important constraint for the crew scheduling in that depot.
3. Maximum time of a pairing is 24 hours in Iranian railways, but in some special cases it can be increased up to 48 hours. (Increasing maximum time of a pairing can increase the rest times between the trips of a pairing.)
4. Minimum time gap between the trips of a pairings is considered to be about 1 hour.
5. Between each two consecutive pairing, it is necessary to consider a minimum time for resting in the crew home depot. This time is dependent to the elapsed time of the first pairing and at most it is considered as 1 day.
6. The number of driving hours of each pairing is considered as 5 to 6 hours in the day and 4 to 5 hours in the night.
7. In preparing a schedule, it is attempted to consider the work fairness in the number of working hours in the day and night, driving a passenger train or cargo one, origin-destination or being border-to-border of a pairing and etc.

In the current study, all the above considerations were considered. All of the passenger trips of Iranian railways which are fallen into a time interval with the length of 4 to 6 days are regarded. Some passenger trips of Iranian railways are long. In the long trips, the origin-destination time is more than 6 hours and therefore it is not possible to guide the train from the first to end time of the trip by only one crew group. Hence, in this research the long pairings were divided to the shorter ones. Dividing the trips was done in the depots nearing the border of regions. Finally, the number of all considered trips in 4 days and 6 days intervals is 1068 and 1602 trips respectively.

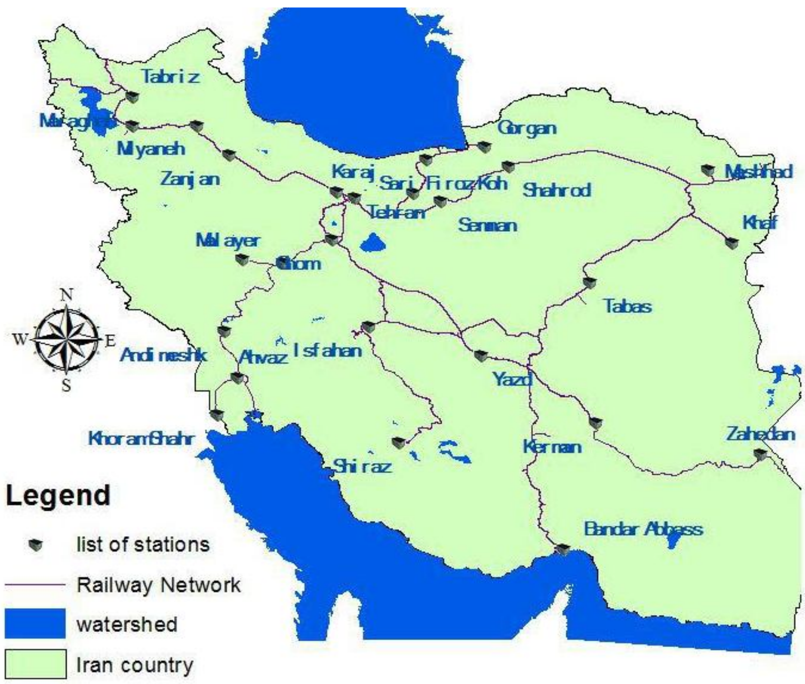

Figure 4. Position of the passenger depots in Iranian railway network

Table 3. Sample information of passenger trips of Iranian railways network

Train No.	Origin	Destination	Minute of Starting	Minute of ending	Duration (Min.)	Frequency
372	Tehran	Mashhad	420	890	470	Daily
373	Mashhad	Tehran	420	895	475	Daily
376	Tehran	Mashhad	480	955	475	Every other day
377	Mashhad	Tehran	475	950	475	Every other day
580	Esfahan	Mashhad	915	2000	1085	Daily
581	Mashhad	Esfahan	935	2015	1080	Daily
480	Tabriz	Mashhad	640	2125	1485	Daily
481	Mashhad	Tabriz	585	2065	1480	Daily
180	Ahvaz	Mashhad	615	2280	1665	Daily
880	Bandarabas	Mashhad	940	2195	1250	Every other day
Tehran		Tabriz	1100	1870	770	Daily
Tabriz		Tehran	1050	1780	730	Daily
Tehran		Zanjan	430	650	220	Daily
Zanjan		Tehran	855	1060	205	Daily
Tehran		Esfahan	1370	1770	400	Every other day
Esfahan		Tehran	1390	1795	405	Every other day
Tehran		Bandarabas	840	1915	1075	Daily
Bandarabas		Tehran	870	1940	1070	Daily
Tehran		Sari	620	1040	420	Daily
Sari		Tehran	1240	1705	465	Daily

To evaluate the first phase algorithm and the model of second phase, 12 scenarios were investigated. These scenarios are shown in Table 4. To solve the problem of these scenarios a computer with Core 2 CPU at 2.66 GHz and 4 GB RAM was used.

As can be shown in Table 3, different scenarios with 4 and 6 days intervals were studied. To maximum covering of the trips, the first phase is divided to the two parts. The difference of these parts is in the maximum allowed time in a pairing. In the first part, the maximum allowed time of a pairing is 24 to 34 hours and so the depth-first algorithm was performed. After running the first part of phase 1, it is observed that some trips cannot satisfy the problem constraints and they are not covered by feasible generated pairings. Hence, in the second part of phase 1, the algorithm was only run for the uncovered trips of the first part. In the second part, the maximum allowed time of a pairing was set to 48 hours to allow generation of long pairings and increasing the possibility of trips covering. For example, In scenario 2 (1602 trips in 6 days), total number of generated feasible pairings in the first part of phase 1 is 9480 with 24 hours as the maximum allowed time of a pairing. But, 202 trips are not covered by any generated feasible pairings. After running the second part of phase 1 with 48 hours as the maximum allowed time of a pairing, the uncovered trips were decreased to 48 trips. These trips cannot generate a sequence with other trips to make a feasible pairing and must be scheduled individually. It is necessary to mention that currently in the empirical schedules of Iranian railways the number of individually scheduled trips is remarkable.

In phase 2, all generated feasible pairings of both parts of phase 2 are considered as input and after solving the mathematical model optimal pairings were obtained. The cost and number of optimal pairings of each scenario were specified. To select the best scenario, the proportion of cost to the number of all trips in each scenario was calculated and shown in Figure 5. In Table 3, for the cases which are specified by "---", it is not possible to solve them because of complete occupying the heap space of the computer. This table shows that by increasing the maximum allowed time in a pairing, the number of feasible pairing is increased such that the software encountered to "not enough memory". According to Figure 5, it seems that scenario 4 (6 days horizon with 28 hours as maximum allowed time in a pairing) has smaller relative cost and so it is a suitable choice for scheduling the Iranian railways crews. Based on obtained results of scenario 4, the proposed model of phase 3 was run for each passenger depot individually. In table 5, sample related results are presented for important depots of Iranian railways.

In each of the solved problem for the presented depots of table 5, the minimum number of required crew groups and assigned pairings to each group are presented. In table 6, the detail of the obtained results of the mathematical model of phase 3 are shown for Isfahan depot as an example.

Table 4. The considered scenarios for phases 1 and 2

				Phase 1								Phase 2		
				Part one				Part two						
Scenario	Time horizon (day)	The number of all trips	Minimum gap time between the trips (Min.)	Maximum pairing time (hour)	The number of all feasible generated pairings	The number of uncovered trips in part one	Solution time (Sec.)	Maximum pairing time	The number of all feasible generated pairings	The number of uncovered trips in part two	The number of optimal selected pairings	Scenario cost	Proportion of cost to the number of all trips	Solution time (Sec.)
Scenario 1	4	1068	60	24	6009	139	1.2	48	144	35	536	584459	548	0.51
Scenario 2	6	1602	60	24	9480	202	2.8	48	238	48	804	867800	542	0.51
Scenario 3	4	1068	60	28	11912	75	4.1	48	37	41	508	565114	529	1.6
Scenario 4	6	1602	60	28	19025	101	7.3	48	61	51	762	836358	518	1.55
Scenario 5	4	1068	60	30	20482	56	5.3	48	26	36	490	561454	525	1.9
Scenario 6	6	1602	60	30	33335	75	12.5	48	42	47	731	830230	522	2.1
Scenario 7	4	1068	60	32	39050	45	9.5	48	8	35	486	559617	523	6.1
Scenario 8	6	1602	60	32	64956	57	25.8	48	12	43			---	
Scenario 9	4	1068	60	34	78133	36	20.2	48	0	36			---	
Scenario 10	6	1602	60	34			---						---	
Scenario 11	4	1068	60	48			---						---	
Scenario 12	6	1602	60	48			---						---	

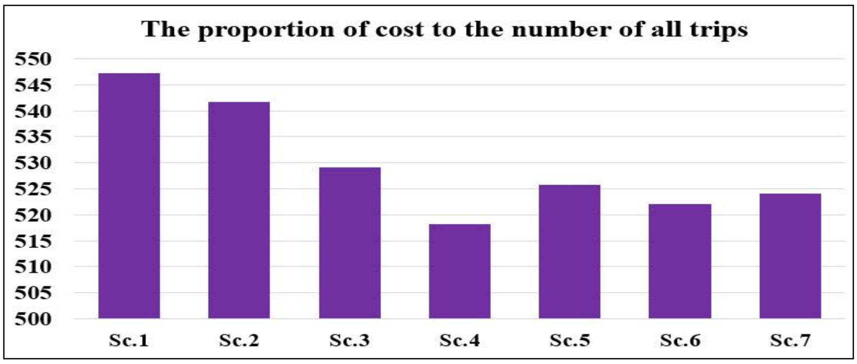

Figure 5. Comparing the proportion of cost to the number of all trips in different scenarios

5. Conclusions

The crew planning and scheduling for passenger trains is currently executed in a manual way by the train experts in some railway systems like Iran. The major shortcoming is that the resolution process has merely been in the realm of human expertise, relying on train expert's judgments, which may not necessarily lead to optimal or even near-optimal solutions from efficiency standpoint. The aim of this study is to propose a comprehensive approach for optimally solving the railway crew scheduling problem. In this approach, the information of different railway trips are considered as input and the problem is divided to three separated phases. In phase I, we generate all feasible sequences of the trips, which are named as the pairings. A depth-first search algorithm is developed to implement this phase. In phase II, the pairings constituting the optimal solution are to be obtained. Both mentioned phases are handled in a centralized decision-making system for the entire railway network. Phase III aims to locally assign the crew groups to the optimal pairings. To solve the problem in phase III, a new mathematical model is developed in this paper. This model is solved by CPLEX 12 software which automatically generates optimal solutions. The model can determine the minimum required crew groups, and optimally assign the crew groups to the selected pairings of each home depot. In order to evaluate the developed algorithm and model, the Iranian railway network is investigated by consideration of all passenger trips of the network. All of the passenger trips of Iranian railways which are fallen into a time interval with the length of 4 to 6 days are regarded. The number of all considered trips in 4 days and 6 days intervals is 1068 and 1602 trips respectively. To evaluate the first phase algorithm and the model of second phase, 12 scenarios are investigated. According to the results, the scenario with horizon of 6 days and 28 hours as maximum allowed time in a pairing, is a suitable choice for scheduling the Iranian railways crews. Based on obtained results of this scenario, the proposed model of phase 3 was run for each passenger depot individually. The results show that the proposed approach is capable of efficiently generating the optimal schedules for the railway crew groups in a reasonable computation time.

Table 5. Some samples of obtained results from the model of phase 3 (Assigning crews to pairings)

Depot	Tehran	Mashhad	Shahrood	Esfahan	Tabriz	Bandarabas	Yazd	Ahvaz
Number of depot pairings (output of Phase 2)	230	168	52	15	17	16	42	14
Minimum required number of crew groups	51	39	14	6	6	6	17	5
Computation time (Sec.)	414	70.3	0.9	0.2	0.17	0.12	1.01	0.16

Table 6. Detail results of applying phase 3 for Isfahan depot

Crew group No.	Assigned pairing No.	Pairing trips No.	Pairing time Duration (Min.)	Crew group No.	Assigned pairing No.	Pairing trips No.	Pairing time Duration (Min.)
1	1407	69 (Esfahan-Yazd) 279 (Yazd-Esfahan)	1085	4	3966	310 (Esfahan-Shiraz) 398 (Shiraz-Esfahan)	1090
1	6492	496 (Esfahan-Tehran) 739 (Tehran-Esfahan)	1677	4	8818	632 (Esfahan-Kashan) 847 (Kashan-Esfahan)	1155
1	18725	1425 (Esfahan-Yazd) 1584 (Yazd-Esfahan)	1085	4	18153	1378 (Esfahan-Shiraz) 1466 (Shiraz-Esfahan)	1090
2	1708	99 (Esfahan-Kashan) 313 (Kashan-Esfahan)	1155	5	9892	744 (Esfahan-Tehran) 918 (Tehran-Esfahan)	1433
2	6057	471 (Esfahan-Shiraz) 655 (Shiraz-Esfahan)	1550	5	15931	1381 (Esfahan-Tehran) 1166 (Tehran-Esfahan)	1155
2	13605	1030 (Esfahan-Shiraz) 1273 (Shiraz-Esfahan)	1677	6	11079	844 (Esfahan-Shiraz) 932 (Shiraz-Esfahan)	1090
3	2779	210 (Esfahan-Tehran) 384 (Tehran-Esfahan)	1433	6	17005	1278 (Esfahan-Tehran) 1452 (Tehran-Esfahan)	1433
3	13170	1005 (Esfahan-Shiraz) 1189 (Shiraz-Esfahan)	1550				

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