A Survey on Problem Models and Solution Approaches to Rescheduling in Railway Networks

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***Abstract*—Rescheduling in railway networks is a challenging problem in both practice and theory. It requires good quality solutions in reasonable computation time to resolve unexpected situations, involving different problem scales, railway network infrastructures, objectives, and constraints. This paper presents a comprehensive survey on different problem models for rescheduling in railway networks by a clear classification. Some frequently used models are described in detail through reviewing their variables and constraints. This paper also focuses on the solution approaches proposed in the literature. The main ideas of the solution approaches with the objectives are described. Based on our review results, the analysis of the problem models used in various problem types and the solution approaches used in different problem models are presented. Conclusion and suggestions for further research to rescheduling in railway networks are drawn toward the end of the paper.**

***Index Terms*—Rescheduling, railway networks, heuristics, meta-heuristics, mixed-integer programming, alternative graphs.**

I. Introduction

The railway traffic system is one of the important parts in a transportation system. Different from other transportation, a train can only run on the assigned tracks and the train driver can only control the train according to the information provided in advance, including route selection, speed limitation, and command activities, etc.

Railway lines and networks are two common structures of the railway infrastructure. The trains, stations, tracks, block sections and signal systems are the basic components of a railway system. There are several types of trains running on the tracks, such as passenger trains with different speeds, heavy cargo trains, and light cargo trains. The types of railway tracks can be unidirectional or bi-directional, single, double or multiple. A block section is a specific length of track segment that is controlled by two signals. At any given time, at most one train is permitted in each block section. The railway signal system is used to control railway traffic safely and to prevent trains from colliding by indicating whether the line ahead is clear or blocked, the speed the train may travel, and the state of the next signal, etc. An operation is the passage of a train through the specified block section and a sequence of operations make up a route of a train.

The management of a railway system can be divided into four levels, which are strategic, tactical, operational and rescheduling [1], [2]. These four hierarchical levels are different in the decision levels and interrelated with each other during the operations. At the strategic level, it is handled by the railway policy makers and usually planned for several years in advance including the pricing strategy, energy utility, infrastructure development, facility upgrade, etc. The strategic level concentrates on planning long term overall resource acquisition. At the tactical level, slot allocation, timetabling, routing, crew scheduling, and rolling stock circulation, etc., will be specified in order to make the railway function according to them. The operational control refers to daily planning work, which is executed not long before the train's departure by the local traffic managers. Rescheduling focus on real-time handling of disturbances when they happen in order to restore the railway networks to normal.

With the increasing demand in railway transportation, the rescheduling problem in railway networks has received more and more attention in recent years. In this paper, we will review the literature of rescheduling in railway networks and discuss the review results. The rest of this paper is organised as follows. The description of the rescheduling problem in railway networks is given in Section II. The classification of problem models, various solution approaches, objectives, and problem instances are comprehensively reviewed in Section III. Further discussions of the different kinds of problem models and solution approaches are presented in Section IV. Section V concludes the paper and presents future research directions on rescheduling in railway networks.

II. Rescheduling in Railway Networks

A typical characteristic of railway networks is that one station can be connected directly with more than two stations, which is significantly different from railway lines. In a railway

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TABLE I
USUAL TACTICS FOR RESCHEDULING

Changing tracks/platforms
Changing arrival/departure times of trains
Changing dwell times of trains at stations
Breaking connections
Changing the train speed
Changing the unplanned stops
Changing the order of trains
Cancellation of trains/Extra trains

network, different railway lines will inevitably interact and influence each other during daily operation. Railway networks are therefore particularly vulnerable to disturbances. When disturbances occur, trains will suffer an inevitably primary delay at their entrance in the control area and conflicts will arise in the control area. Due to the interaction between trains, the conflicts will lead to additional delays to other trains in the network, which is called secondary delays. Although a good timetable has the ability to absorb minor disturbances by using the buffer time in real time, serious disturbances and technical failures will create delays that make serious deviations from the timetable. In a highly utilized railway network, even a small disruption can spread out rapidly throughout the whole network and affect significantly the train schedules. Therefore, it is very important and necessary to respond to the disturbances for recovering railway networks to normal.

According to the description above, the rescheduling problem in a railway network can be defined as follows [3]–[7]: considering the affected trains in a railway network and the original schedule for these trains including the timetables, stops and stations, the assignment of tracks, platforms, drivers, etc., rescheduling is to find a new feasible schedule by satisfying the objectives such as minimizing the delays and costs and meeting the necessary operational or commercial constraints. Table I summarizes common tactics used by the train dispatchers in rescheduling to meet the requirements. One can find that the rescheduling problem in railway networks includes several aspects and the rescheduling problem can be studied from different perspectives.

In this paper, we follow the classification method proposed by Pacciarelli in [8] for the existing rescheduling literature. Assuming that disturbances are arising at time t with known static and dynamic information about the railway network, rescheduling is to find a new feasible schedule without conflicts for the time window $[t+a, t+b]$. Problem types for rescheduling in railway networks are therefore classified by the values of a and b. Within some ranges, typical values for real-time rescheduling are $a \leq 2$ minutes and $b \leq 45 \sim 60$ minutes. Delay management is typically associated with decisions about transfer connections, with values $2 \sim 3 \leq a \leq 10 \sim 15$ minutes and $b \leq 2 \sim 3$ hours. Once $b \geq 2 \sim 3$ hours, the problem belongs to disruption management. Fig. 1 shows the relationship between problem types and time windows. By taking into account the topics of the reviewed papers, the problem types discussed in our review are conflict detection and resolution (CDR), disturbance recovery, real-time rescheduling, delay management, train dispatching, crew/vehicle/timetable rescheduling, and disruption recovery. Here, CDR and disturbance recovery also belong to the problem type of real-time rescheduling. Train dispatching, crew/vehicle/timetable rescheduling, and disruption recovery fall in the problem type of disruption management [9].

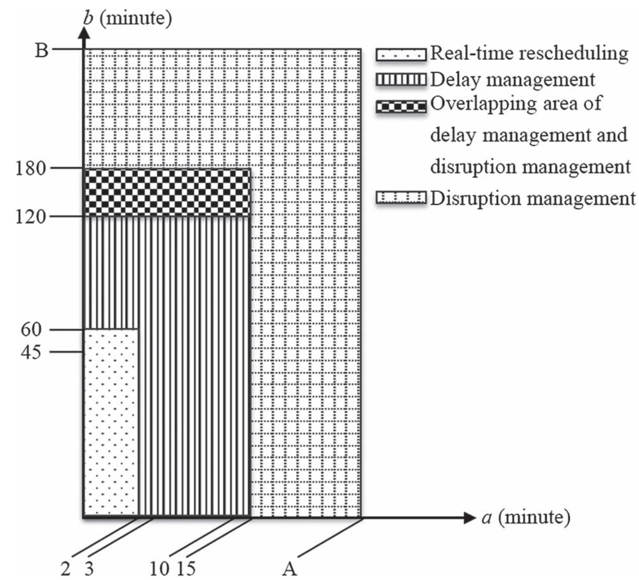

Fig. 1. The relationship between problem types and time windows for new feasible schedule. In the figure, A and B denote the numbers larger than 15 minutes and 180 minutes, respectively.

The rescheduling problem in railway networks is a challenging problem that is difficult to handle without the help of computer based decision support systems. Rescheduling approaches in railway networks should at least possess two features, which are robustness and timeliness. A robust approach in this case means that the rescheduling results obtained by the approach should be as similar as possible to the original schedule under different situations. As the disturbances happen stochastically and there is usually limited time for train dispatchers to determine solutions, rescheduling approaches must be very quick; otherwise, it may cause further knock-on delays in railway networks.

There have been some reviews on the topic of scheduling or rescheduling in railway systems [1], [2], [9]–[11]. Our paper has added to this body of literature by carrying out a far more comprehensive review of more recent papers in rescheduling. Our review differs from previous ones in at least five aspects, including whether and to what extent the mathematical models, non-mathematical models, and solution approaches were studied, the publication year, and the number of references. The comparison is summarized in Table II. [9] and [12] are the latest reviews related to the topic of rescheduling in railway systems. [9] only discussed the mathematical recovery models and algorithms, mainly for three kinds of rescheduling problems, including timetable rescheduling, rolling stock rescheduling and crew rescheduling. [12] focused only on approaches for online dynamic rescheduling problems in railway traffic management. [10] and [11] only selected a few literature dealing with the delay management. In [1], the authors mainly presented the scheduling and rescheduling railway operations from four levels. The earlier review [2] put the emphasis on

TABLE II
COMPARISON AMONG THE PUBLISHED REVIEWS AND THIS PAPER

	[12]	[9]	[10]	[11]	[1]	[2]	This paper
Mathematical models	⋆	⋆	★	∗	∗	∗	★
Non-Mathematical models	-	-	-	∗	∗	-	⋆
Solution approaches	★	★	⋆	-	∗	★	★
Publication year	2014	2014	2013	2012	2012	2006	in press
Number of references	82	90	11	22	117	76	128

The symbols ★, ⋆ , and ∗ mean that the row item is more detailed, detailed, and less detailed in the corresponding review paper. The symbol '-' means that the row item was not mentioned in the corresponding review paper.

TABLE III
CLASSIFICATION OF PROBLEM MODELS

Integer Programming (IP)	[13]–[28]
Mixed-Integer Linear Programming (MILP)	[29]–[54]
Mixed-Integer Nonlinear Programming (MINLP)	[55]
Constraint Programming (CP)	[56]–[62]
Alternative Graph (AG)	[63]–[84]
Fuzzy Petri Net (FPN) and Expert System (ES)	[85]–[92]
Discrete event model	[93]–[101]
Simulation model	[102]–[109]
Other models	[110]–[115]

the solution approaches for railway traffic scheduling. The aim of our paper is to classify and compare the problem models, including mathematical models and non-mathematical models, solution approaches, and problem types for rescheduling in railway networks in more detail. We review nearly 130 papers in order to present a comprehensive picture of the current state-of-the-art in different aspects of rescheduling in railway systems.

III. PROBLEM MODELS AND SOLUTION APPROACHES

In order to solve the rescheduling problem, the model of railway network topology, such as the infrastructure, as well as the traffic situation, and the traffic constraints should be identified at first, which will form a mathematical model with a set of variables and constraints, a graph-based model, or a simulation model, etc. The classification of problem models in our reviewed literature is given in Table III. From Table III and Fig. 2, we can find that the integer programming (IP), mixed integer linear programming (MILP), and alternative graph (AG) models are the three most used models for the rescheduling problem in railway networks. Thus, more attention will be paid to these three models in our review.

Among the reviewed papers, not only different models were studied, but also diverse types of rescheduling problems, e.g., delay management, conflict resolution, disturbance management, real-time rescheduling, online timetable rescheduling, crew rescheduling, etc, were investigated. Based on the problem models and problem types, quick and robust approaches with good performance are needed to solve the rescheduling problem. The problem scale varies greatly across different papers according to the scope of disturbances, the influence factors

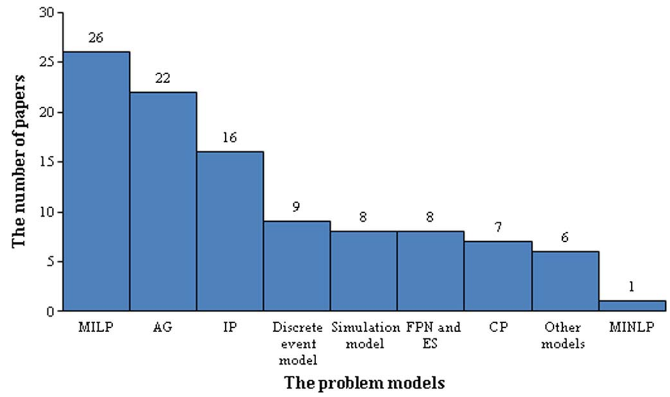

Fig. 2. Number of the papers in each problem model.

of disturbances, and the rescheduling tactics. Therefore, the solution approaches need to balance between the computation time and the solution quality. In the following sections, the objectives, solution approaches, problem instances, and characteristics of the problem models are discussed in detail under each category of problem models.

A. Integer Programming (IP) Model

Regarding the IP model for rescheduling in railway networks, the decision variables are usually binary variables and non-binary integer variables. The rescheduling tactics can be represented by binary decision variables, such as the connection maintenance, the priority of two trains, sequences of trains, assignment of resources, etc. The arrival and departure time of trains can be represented by non-binary integer values by denoting them in discrete time intervals. The delays are also treated as integer variables. The constraints in railway network management are generally expressed by the equality or inequality constraints in the IP model. From the decision variables and constraints of an IP model, one can understand which kind of rescheduling tactics were considered and the scale of the considered problem. The summary of binary and non-binary integer variables and the sets of constraints are given in Table IV. Table V summarizes the objective functions, problem instances and sizes, and the approaches for rescheduling based on the IP model. The main ideas of the approaches are also extracted from the related papers and given in Table V.

B. Mixed-Integer Programming (MIP) Model

Regarding the MIP model for rescheduling in railway networks, the arrival and departure times and delays are represented as continuous decision variables, which is the main difference from the IP model. The binary decision variables are similar to those in the IP model, which can be found from the summary of binary and continuous decision variables in Table VI. As can be seen, the decision variables are diverse among different papers, which shows different levels of detail in the MIP models. The sets of constraints for modelling the problem in each paper are also shown in Table VI and they also vary across the models. In Table VII, the objectives, solution approaches, main ideas of the approaches, and problem

TABLE IV
SUMMARY OF BINARY/INTEGER DECISION VARIABLES AND THE SETS OF CONSTRAINTS IN THE IP MODEL

	Decision variables (binary)	**Decision variables (integer)**	**Sets of constraints (equalities/ inequalities)**
[13]	If a connection is maintained or not.	Delay of an event.	3(0/3)
[14]	If changing activity is maintained or not; If an event takes place before another event or not.	Actual time of event.	5(1/4)
[15], [16]	If changing activity is maintained or not;	Actual time of event.	4(0/4) [15]; 5(1/4) [16]
[17]	If changing activity is maintained or not; If an event takes place before another event or not; If an event takes place before or at time t or not (packing-based) / if an arrival and corresponding departure are assigned to platform or not (assignment-based).	Actual time of event.	6(packing-based)(1/5) 9(assignment-based)(2/7)
[18], [19]	If a connection is maintained or not; If an arc is used by passengers or not.	Actual time of event; Arrival time of passenger.	8(3/5)
[20]	If a train waits for another train or not; If a drift shift is included in the solution or not.	The start time of a work on a train service; The amount of time a train remains idle upon the completion of a piece of work; The amount whose start time precedes or follows the originally scheduled start time;	14(9/5)
[22]	The circulation of trains; If a departure event takes place before anther event, the two events use the track in the same direction; If an arrival event takes place before another event, both events are at some station;	The delay of event.	9(3/6)
[23]	The amount of resource on the directed link	-	5(4/1)
[24]	If the driver takes on the candidate duty or not	-	2(1/1)
[26]	If blocking-stairway is assigned or not; If train has a connection to another train or not.	-	7(1/6)

In the table, the symbol '-' means that this kind of variables was not used in the corresponding paper.

instances and sizes are summarized. It should be noted that the sets of decision variables and constraints listed in Table VI are just for one train or one event. With the increasing number of trains considered in the problem model, the problem's scale will increase dramatically. The rescheduling problem based on the MIP model has been proved to be NP-hard [2], [38], [56], [106]. Since rescheduling in railway networks aims to restore the railway system, it demands good solutions within less computational time, which has been considered as a major challenge for the solution approaches in the literature, as shown in Table VII. From the operational research (OR) view, both MILP and MINLP models belong to the MIP model. The MINLP model implies that the objective function and constraints of the model are nonlinear. As it is more difficult to solve a MINLP, one can see that, among all the reviewed papers, only one paper used the nonlinear objective function. In order to obtain the MILP model, the nonlinear constraints are usually linearized by mathematical approaches [53].

C. Constraint Programming (CP) Model

Acuna-Agost indicated that the MIP model for rescheduling in railway networks is unable to solve large instances as the number of variables and constraints increases rapidly with the number of trains and stations [56]. An alternative model is a CP model since it incorporates techniques to reduce the variables and constraints. The main components in the CP model for formulating rescheduling are the data sets, parameters, decision variables (including continuous and binary variables), traffic constraints, and the objective function, which are similar to those in an MIP model. However, a CP model can describe the problem more naturally because of the definitions of some variables and constraints, the representation of the order of trains, and the use of tracks. These make a CP model require much fewer variables and constraints than an MIP model. A new sequence of trains will be obtained usually by heuristics to solve the CP model under the scheduling constraints. The summary of different approaches to rescheduling based on a CP model is given in Table VIII.

D. Alternative Graph (AG) Model

The AG is a generalization of the disjunctive graph and can be used as an effective tool to model complex job shop scheduling problems (JSSPs) [116], [117]. The AG is represented by three kinds of elements, which are a set of nodes, a set of fixed directed arcs, and a set of pairs of alternative directed arcs. The length of an arc can be positive, null or negative. In an AG model, a selection means a set of arcs from alternative arcs and at most one arc in each pair of alternative arcs can be selected for one route. For a given consistent selection, there may not exist an extension of this selection, while in the disjunctive graph there always exists an extension, which is an important difference between the AG and disjunctive graph models [63].

According to the block constraints in the railway networks, at most one train is permitted to run in a block section at a time. A conflict will occur if two or more trains require the same block section at the same time and should be solved by the train dispatchers. D'Ariano *et al.* defined this kind of conflicts as the real-time conflict resolution problem (CRP), which is an online problem aiming to find a conflict-free schedule compatible with the real-time status of the network with the smallest possible delay [64]. They pointed out that CRP is very similar to the no-store JSSP and the latter problem could be modeled by an AG model [117]. The correspondence of the concepts can be established between CRP and the no-store JSSP. A track

TABLE V
SUMMARY OF APPROACHES TO RESCHEDULING BASED ON THE IP MODEL

	Objectives	Approaches	Main ideas of the approaches	Problem instances and sizes
[13]	Minimizing the sum of all delays over all customers	1. IP solver (GNU linear programming kit (GLPK)); 2. Enumeration method	1. -; 2.Decompose the problem iteratively into sub-problems, and solve them bottom-up	Harz region in the center of Germany, 158 railway stations, 1101 trains, a day time window.
[14]	Minimizing the delay over all vehicles and minimize the number of missed connections	First scheduled, first served (FSFS), First rescheduled, first served (FRFS), FRFS with early connection fixing (FRFS-FIX), FSFS-FIX	Fix the order of trains in advance and solve the remaining incapacitated delay management problem	Harz region in the center of Germany, 598 stations, 92 trains, 30 lines, 8 hours time window.
[15]	Minimizing a combination of (weighted) dropped connections and (weighted) train delays	First-come-first-served (FCFS), FRFS, B&B	Replace the headway constraints by simple precedence constraints	Harz region in the center of Germany , 183 stations, 1962 trains.
[16]	Minimizing the sum of all delays over all customers and the weighted sum of all missed connections with a penalty of the time period	FSFS, FRFS, FRFS-FIX, FSFS-FIX	Fix the order of trains in advance and solve the remaining incapacitated delay management problem	Harz region in the center of Germany, 598 stations, 92 trains, 30 lines, 8 hours time window.
[17]	Minimizing the sum of all delays over all customers and the weighted sum of all missed connections with a penalty of the time period	CPLEX and an iterative heuristic approach	By the iterative procedure to improve the platform assignment with respect to the current delays of the trains at each station in each step	The railway network in the Randstad; Case 1: 10 stations, 117 trains; Case 2: 16 stations, 168 trains.
[18]	Minimize the arrival times of the passengers	CPLEX and a modified Dijkstra's algorithm	Find a better lower bound on the arrival time to improve the solution process.	Part of the railway network in the Netherlands, 2 hours time window; Case 1: 7 trains; Case 2: 117 trains; Case 3: 168 trains; Case 4: 282 train.
[19]	Minimizing the weighted sum of delays	Three heuristic methods;1.simple dispatching rules heuristic(Waiting Time Rule); 2. the classical delay management model without passenger rerouting; 3.updates the parameters of the classical model iteratively.	Use the no-wait policy as the benchmark of the proposed heuristic approaches	Netherlands Railways; Case 1: 10 stations, 117 trains; Case 2: 34 stations, 284 trains; Case 3: 34 stations, 284 trains; Case 4: 16 stations, 168 trains; Case 5: 82 stations, 404 trains; Case 6: 82 stations, 404 trains.
[20]	Minimizing the deviation from the existing schedule with minimum cost increase from the adjusted crew shifts	B&B with column and constraint generation	Reduce the number of constraints; speed up the solution process by hot-starting from the previous solution.	Case 1: South Island Coal route, 47 stations and sidings, 3 crew bases, 17 trains; Case 2: Wellington Metro line, 36 trains, 18 hours time window.
[22]	Maximizing the number of trips, possibly with delay	CPLEX	Reducing the number of precedence constraints by fixing some variables	Subway line U6 in Vienna; 24 stations.
[23]	Minimizing the sum of all the flow costs referring to the resources (crew or vehicle)	Two-phase solution approach including the heuristic flow modification and local search technique	Using the partial exchange heuristics to generate a feasible solution by modifying the original schedule and then using local search to improve the evaluation value	Japanese railway; 786 trains and 185 vehicles.
[24]	Minimizing the total cost of the selected duties	CPLEX with column generation technique	Alternatively enumerate candidate duties and optimize rescheduling	Japan's highest frequency of freight train operation; 413 trains.
[25]	Minimizing the sum of all the flow costs referring to the resources (crew or vehicle)	Lagrangian relaxation method	-	-
[26]	Maximizing customer satisfaction measured as punctuality and reliability	Model predictive control approach	A closed loop system for the model-predictive control approach, including forecast evolution of system state, resource conflict detection and optimization resolution, disposition schedules.	The central railway station area of Berne, Switzerland; 13 platforms, 900 switches, the average number of considered routes for the arrival (or departure) of a train was 175.

TABLE VI
SUMMARY OF BINARY/CONTINUOUS DECISION VARIABLES AND THE SETS OF CONSTRAINTS IN THE MILP AND MINLP MODELS

	Decision variables (binary)	**Decision variables (continuous)**	**Sets of constraints (equalities/ inequalities)**
[29], [30]	If an event uses a track or not;	The start time of an event for a train;	17(3/14) [29], [30]
[31]	If an event for a train has missed its connecting event or not; If an event on a block occurs before or after another event or not.	The start time of an event; The end time of an event; The delay of an event; Time difference between end of an event for a train and start of its connecting event.	11(1/10)
[32], [33]	If an event uses a track or not;	The start time of an event for a train;	23(6/17)
[34], [35]	If an event occurs before another event (as in the initial timetable) or not; If an event is re-scheduled to occur after another event or not.	The end time of an event for a train; The delay of an event for a train.	
[36], [53]	If an event occurs before another event (as in the initial timetable) or not; If an event is re-scheduled to occur after another event or not; If a train reaches its final considered stop with a delay larger than the settled time units or not;	The end time of an event for a train; The delay of an event for a train.	25(6/19) [53] 28(5/23) [36]
[37]	If an indivisible series of wagons carries out programmed movement of passengers between two stations or not.	The departure time of a service from its first station; The time at which a unit will finish service; The arrival time at a station of service; The delay with respect to the official departure time.	8(5/3)
[38]	If a train is assigned to the a track of a segment or not; If a train departs earlier than another train at the end station of a segment or not; If a train arrives earlier than another train at end station of a segment; If a train has a dwelling mode at a segment or not;	Departure time of a train at the end station of a segment; Arrival time of a train at the end station of a segment; Difference between original arrival time and actual arrival time.	19(2/17)
[39]	If one train passes a node before another train or not;	The arrival time of a train; The departure time of a train.	5(0/5)
[40]–[43]	The order of two trains	Time instant at which a train departs from station.	5(0/5) [40] / All the constraints are represented by a matrix [41]–[43]
[44]	If train reaches its final considered stop with a delay larger than the settled value or not; If a train use a track at a station or not; If the departure time of a train at a station is earlier than the departure time of another train at another station to original timetable or not; If the departure time of a train at a station is changed to occur after the departure time of another train at another station;	The new departure time of a train at a station after adjustment; The new arrival time of a train at a station after adjustment; Delay of a train at a station; The fuzzy number for the objective and constraints.	12(3/9)
[45]	If the connecting passengers from the feeder train actually can board the connecting train or not;	The actual arrival time. The actual departure time.	8(0/8)
[46]	If a given train passes before another train or not; If a train uses a track or not; If a train stops in the new schedule while it shouldn't in the original one or not;	The actual arrival time. The actual departure time.	5(0/5)
[47], [48]	If a route is assigned to a train or not; If two trains meet at the a point or not; If two trains meet at the 2-station or not; If a train takes the siding at the 2-station or not; If a train travels on a route affected by a MOW (Maintenance of Way) and train traverses a path after the MOW window or not; If a train travels on a route affected by a MOW and the train traverses a path before the MOW window or not.	The time when a train reaches a station. The delay of a train on a route; The schedule deviance for a train; The deviance at the terminal of a train; The time spent by a train on edge.	14(4/20)

segment and a train are regarded as a no-store machine and a job respectively. A node in the AG model represents the time at which a given train enters a given block section. A block constraint can be modeled by a pair of alternative arcs in the AG model. The AG model can also handle the traffic constraints in train scheduling and traffic regulation rules when dealing with the real-time railway network management [63], [64]. The longest path in an AG model is equivalent to the maximum propagated delay of the corresponding train sequencing [64]. Therefore, the objective of CRP based on the AG model is to minimize the length of the longest path satisfying the fixed and alternative precedence relations. A detailed corresponding relationship among these models is given in Table IX. Table X shows the methods for treating these rules and constraints.

TABLE VI
(Continued.) SUMMARY OF BINARY/CONTINUOUS DECISION VARIABLES AND THE SETS OF CONSTRAINTS IN THE MILP AND MINLP MODELS

	Decision variables (binary)	Decision variables (continuous)	Sets of constraints (equalities/ inequalities)
[50]	If a train uses a track of a segment or not; If a train is scheduled earlier than another train at a segment on the same or conflicting tracks or not; If a train is scheduled later than another train at a segment on the same or conflicting tracks or not; If there is positive or negative difference between the first and third consecutive segments for scheduling two same trains or not; If a train and another train have a meet-pass event at a segment or not; If a train exits a segment prior to the end of the planning horizon or not; If the entry time of a train at a segment is larger the end time of MOW or not.	Entry time for a train at a segment; Exit time for a train at a segment; Delay for a train at a segment; Schedule deviance beyond 2 hours for a train at a segment; Time wait time deviance for late (early) arrival beyond the 4-hour window for a train; Unpreferred track time (if any) for a train at a segment; Equals to the exit time for a train at a segment if a train exits a segment prior to the end of the planning horizon.	33(8/25)
[51]	If a path is used in the solution or not.	The deviation of a train path	2(1/1)
[52]	If a train arrives immediately before another train at a station or not; If a train departs immediately before another train from a station or not; If a train departs immediately before the arrival of another train at a station; If a train arrives immediately before the departure of another train from a station or not; If a train arrives immediately before another train at a station or not; If a train departs immediately before another train from a station or not; Two Conflict detection variables for UP trains; Two Conflict detection variables for DOWN trains; If schedule of an UP train is conflicted because of disruption or not; If schedule of a DOWN train is conflicted because of disruption or not.	Actual arrival time of a train at a station; Actual departure time of a train from a station.	13(3/10)
[54]	If a train uses a track or not; If a train uses a track-circuit before another train or not;	Maximum secondary delay suffered by any train; Secondary delay suffered by a train when completing its route. Time in which a train starts the occupation of track-circuit along a route; Delay suffered by a train in track-circuit along a route; Time in which track-circuit starts being utilized by a train; Time in which track-circuit ends being utilized by a train;	19(7/12)
[55]	If one train and another train meet of pass between two points or not; Two dummy variables to assure the meet-pass logic.	The arrival time of a train; The departure time of a train.	8(1/7)

Based on the AG model, the complexity of CRP depends on the number of alternative pairs, which are regarded as binary variables in an integer linear programming model [73]. The number of track segments and trains in real-world instances may be hundreds or thousands, which will result in a huge no-store JSSP. As reported in [64], for instances with 54 trains running in a one hour timetable and 108 trains in a two hours timetable, the number of alternative arcs are more than 8000 and 30 000 respectively. It can be seen that with the increasing scale of networks, the number of alternative arcs will increase rapidly, which is a real challenge.

By adopting the blocking time theory for modeling track occupation and signaling constraints and the AG model, the CRP has been studied by considering diverse policies and different approaches [63]–[70], [73]–[79], [118]. An advanced real-time train dispatching support system, called ROMA (Railway traffic Optimization by Means of Alternative graphs), which is based on an AG model, was implemented to support dispatchers in the everyday task of managing disturbances [67], [68], [71]–[73], [76]. In [119], a stability analysis of the optimal rescheduling solution was studied within a stochastic and dynamic environment based on the ROMA framework and a microscopic railway simulation model. Table XI summarizes different approaches to rescheduling based on the AG model.

E. Fuzzy Petri Net (FPN) and Expert System (ES) Models

Train dispatchers have rich professional knowledge and experience to control the railway in their minds. It is possible to capture their skills by a set of knowledge rules and use them in a computer based system in order to produce any possible dispatching options. The FPN and ESs provide suitable tools

TABLE VII
SUMMARY OF APPROACHES TO RESCHEDULING BASED ON THE MILP AND MINLP MODELS

	Objectives	**Approaches**	**Main ideas of the approaches**	**Problem instances and sizes**
[29] / [30]	1. Minimizing the total final delay of the traffic; 2. Minimizing the total cost associated with delays when trains arrive at their final destination	Heuristic approach with four strategies /Heuristic approach	Allow swaps of tracks but maintain order; Allow swaps of tracks and implicit change of order; Allow a number of order swaps for specific segments; Allow all changes / Allow a number of order swaps for specific segments considering the secondarily disturbed trains	A part of the Swedish railway traffic network; 169 stations and meet points, 92 freight trains and 466 passenger trains. / The region of Norrkoping traffic control centre, Sweden; 74 freight trains, 211 passenger trains and 28 service trains.
[31]	Minimizing the total delay of the traffic system; minimizes the total cost	CPLEX, Tabu search (TS), and simulated annealing (SA)	Iterative two-level process; Relax the MIP model to LP model and solve the LP problem by CPLEX for optimizing the allocation of start and end times for each train and the blocks it will occupy; SA and TS for determining the order of trains on blocks	Railway network in Blekinge Kustbana, Sweden; one train departing every hour.
[32]–[35]	Minimizing the total final delay [32]/ Minimizing the sum of the final delay of all trains [33]–[35]	Greedy algorithm [32], [33]/ parallelized of the improved Greedy algorithm [34]/ Greedy algorithm [35]	Using the depth-first search quickly find a feasible solution by building up a first complete branch of the tree and then branch the tree according to a set of criteria. [32], [33] / Improving the greedy algorithm in [32], [33] by a more efficient branch method and implemented a parallel version of the improve greedy algorithm [34] / Three different strategies used in the greedy algorithm in [32], [33]	Norrkoping traffic district in Sweden; 28 stations. [32]–[35].
[36]	Minimizing the total rescheduling cost	Statistical Analysis of Propagation of Incidents (SAPI) and Iterative SAPI	Reduce the search space by estimating the probability that an event, one step of the itinerary of a train, is affected by a set of incidents	Case 1: a real French line connecting two cities; 7 hour time window, 67 trains passing through 43 stations; Case 2: a real Chilean network composed of 140 trains, 49 stations, 24 hour time window.
[37]	Maximizing the number of passenger transported	Heuristic approach	Reducing the search space by means of a backtracking process to select the best evaluated solutions realized by a depth-first search based B&B implicit enumeration procedure.	The regional railway network in Asturias; 15 trains.
[38]	Minimizing the total weighted deviation between original and rescheduled timetables of trains	Heuristic approach	Use the column generation algorithm to solve the LP-relaxation of the MIP model; and then reduce the problem size by fixing the most promising column and use a heuristic approach to obtain a feasible train schedule of a segment	The network in the Seoul metropolitan area; 66 trains per hour in each direction of a segment, 23 stations.
[39]	Minimizing the sum of all the trains arrival times to their destination nodes	B&B	B&B with the sequence-fixing to reduce the explore tree nodes	A portion of the railway network near downtown Los Angeles.

TABLE VII

(Continued.) SUMMARY OF APPROACHES TO RESCHEDULING BASED ON THE MILP AND MINLP MODELS

	Objective function	**Approaches**	**Main ideas of the approaches**	**Problem instances**
[40]–[43]	Minimizing the sum of all predicted delays and the penalty for all broken connections and switched train orders	GA [40], [41]/ permutation-based algorithm [42]/ Six free and commercial MIP solvers [43]	Use a track-based ordering to speedup the solution process [43]	A simplified version of the Dutch railway system; 1 hour cycle time window, 40 stations, 164 trains [40], [41]. / Simulation data, 1 hour time window, 3 stations, 4 trains [42]./ The model of the Dutch railway system; 1 hour time window, 41 stations [43].
[44]	Minimizing the delay cost and the number of seriously impacted trains	CPLEX	-	Beijing to Shanghai high speed line, seven stations, 52 trains, starts at 6:30 am and ends at 11:30 pm.
[45]	Minimizing the total unexpected waiting time of all passengers within the relevant network and time period	Heuristic local rule-based dispatching strategies	Use the heuristics on the waiting time, wait decision, the connection decisions of the passengers, etc.	One region of the long-distance network of Deutsche Bahn; 4 hours time window, 24 stations; 5 hours window, 25 stations.
[46]	Minimizing the total accumulated delays	CPLEX with B&B for linearly programming; EA; hybrid of CPLEX and EA	As the hybrid method is concerned, use the EA to quickly obtain a good solution of permutation, and then regarding the good solution as the initial solution of CPLEX	A railway between Tours and Bordeaus; 99trains.
[47], [48]	Minimizing the total delays and the deviance	Greedy heuristic approaches with CPLEX [47]/ Fixing heuristics with CPLEX [48]	Reducing the solution space: Limit the number of routes by pre-selecting a 'most promising one' for each train; let the model determine the routes only for subsets of trains. [48]/Fixing routes or fixing trains [48]	Simplified network; 12, 18, 20 trains [47]./ 12 hours time window, 12-30 trains [48].
[50]	Minimizing the total costs incurred by the train delay and the deviance	Decomposition algorithm	Iteratively execute the three steps: order the trains by entry time, only schedule the earlier trains, fix the corresponding event variables or train variables	12, 18 trains
[51]	Minimizing the total deviation weighted by train priority for all trains	branch-and-price approach	A dynamic update procedure from rerouting a small number of train paths, decompose the problem to a master problem and a pricing problem; using the branch-and-price approach to exploit the flexibility of the model.	Complex junction in Germany; Case 1: 1 hour time horizon, 31 trains; Case 2: 2 hours time horizon, 66 trains
[52]	Minimizing the weighted sum of the difference between the actual and scheduled	GNU Linear Programming Kit (GLPK) solver	-	4 stations and 6 trains
[53]	Minimizing the total rescheduling cost	Right-shift, Local Search, Iterative Local Search	Limit the search space around the original non-disrupted schedule by hard and soft fixing of integer variables with local-branching-type cuts	Case 1: a real French line connecting two cities; 7 hour time window, 67 trains passing through 43 stations; Case 2: a real Chilean network composed of 140 trains, 49 stations, 24 hour time window.
[54]	Minimizing the total secondary delay suffered by trains	CPLEX	The infrastructure is represented with fine granularity, which can model either the route-lock sectional-release or the route-lock route-release interlocking system.	Case 1: the junction named triangle of Gagny, 3 trains and 10 trians; Case 2: the control area including the Lille-Flandres station, a Wednesday timetable including 589 trains.
[55]	Minimizing the total variance in delays	Heuristic approach	Decompose the problem into master program and subprogram and solve them repeatedly and alternately. Use an efficient network-flow algorithm to get the continuous variables and use two local search methods to obtain the order of trains.	A portion of a major U.S. railroad.

TABLE VIII
SUMMARY OF APPROACHES TO RESCHEDULING BASED ON THE CP MODEL

	Approaches	Objectives	Problem instances and sizes
[57]	B&B	Minimizing the sum of train delays caused by conflicts	Junction of Pirrefitte Conesse North of Paris; Up to 24 trains.
[59]	Two heuristics,	1. Minimizing the number of station visits affected	A segment of the China railway.
	The smallest-domain-first heuristic and the most-constrained-first heuristic	2. Minimizing passenger delay	
[60]	Chronological strategy	Minimizing the total delay according to the constraints posted	Simulation datasets; 5 stations, up to 25 trains.
[61]	Heuristic, dispatching rule, and B&B in three stages respectively.	Minimizing the total delay according to the constraints posted	Simulation datasets; 5 stations, up to 30 trains.
[62]	An one-step B&B, local search procedure, and B&B in three stages respectively.	Minimizing the total delay according to the constraints posted	Simulation datasets; 5 stations, up to 30 trains.

TABLE IX
CORRESPONDING CONCEPTS AMONG THE RAILWAY NETWORKS, NO-STORE JOB SHOP SCHEDULING, AND ALTERNATIVE GRAPHS

Railway networks	No-store job shop scheduling	Alternative graphs
A track segment	A no-store machine	-
A train	A job	-
Block section	A sequence of machines	-
Blocking constraints	The absence of buffers between machines	-
Passing of a train through a particular block section (an operation)	Processing of a job	A node
Route of a train	A chain of jobs	A chain of nodes
The constraints that each block section can only pass one train at a time	The constraints that each machine can process only one operation at a time	Alternative pairs
the running time of a train through the block section	Fixed precedence relations	Fixed arcs
The maximum secondary delay of the associated schedule	The completion time of the last operation	The related longest path in the graph

In the table, the symbol '-' means that there are no corresponding items.

TABLE X
METHODS FOR TREATING TRAFFIC CONSTRAINTS IN TRAIN SCHEDULING AND TRAFFIC REGULATION RULES IN AN AG MODEL

Type of constraints	Treating Methods in an AG model	Description of constraints
Minimum speed constraint	Adding another fixed arc with negative length in the opposite direction between two nodes	The minimum speed of a train running within a block section
Passing constraint	Inserting a fixed arc regarding the given time as the length between the start node of AG and the passing node	A train must pass through a node only after a given time
Stop and departure constraint	Modeled by a pair of nodes linked by a fixed arc regarding the minimum dwell time as its length	A train stops at a location and then departure after a given time
Connection constraint	Adding a fixed arc from the node of associated with the train B to the node of associated with train A regarding the minimum connection tim as its length	Train A leaves its location in the minimum connection time after train B arrives another location
Out of order constraint	Adding a pair of alternative arcs between the start node of AG and the two nodes of the block section regarding the value of interval as the lengths	If a block section is unavailable for trains in a given time interval
Precedence constraint	Adding a fixed arc with suitable length from the node associated to the arrival of the former train to the node associated to the departure of the latter one	The latter train must wait for the arrival of the former one before departing in case the
Meeting constraint	Adding two fixed arcs of suitable lengths between two nodes associated with the two trains	The minimum dwell time for two related trains staying at a given station for exchanging passengers or goods

to model the train dispatchers' expertise. In an FPN model, the train dispatchers' knowledge and experience about the dispatching actions can be modeled by fuzzy rules of the IF-THEN type. All the fuzzy IF-THEN rules form a fuzzy rule base. The rule base should be limited to a certain size; otherwise, the system will be out of control [110]. An ES is a computer program system that has experts' knowledge to solve complex problems in a narrow domain by emulating the experience and expertise of a human expert. An ES can be implemented based on an FPN.

The decision rules of train dispatchers and the infrastructure of a railway network were modeled by a Petri net (PN) or FPN in [85], [88], [89]. Fay used an ES for knowledge acquisition and combined the ES with FPN to design a fuzzy knowledge-based system for railway traffic control [87]. Schaefer and Pferdmenges introduced an ES based real-time train dispatching system, which can automatically detect and resolve conflicts [90]. In [91] and [92], an ES was used to automate the train management and online rescheduling in railway networks.

F. Discrete Event Model

The discrete event model is a kind of dynamic model, which means the dynamic (new or updated) information will be used during the solution procedure [93]–[97], [102]. In the studied discrete event models, the railway system is described by the

TABLE XI
SUMMARY OF APPROACHES TO RESCHEDULING BASED ON THE AG MODEL

	Objectives	**Approaches and main ideas**	**Problem instances and sizes**
[63]	Minimizing the exit delays	Heuristics(Avoid Most Critical Completion time (AMCC)) for reordering, heuristics for rerouting, and a speed adjustment procedure	Case 1: Schiphol bottleneck; 27 trains per hour per direction; Case 2: The junction at Lage Zwaluwe; 4 trains.
[64]	Minimizing the maximum secondary delay for all trains at all visited stations.	Truncated B&B with two dynamic implication rules for reordering	Schiphol bottleneck; 1-hour circle time window, 54 trains.
[65]	Minimizing the maximum consecutive delay	First-in-first-out (FIFO), First-out-first-in (FOFI), AMCC, B&B [64] for reordering, and a speed adjustment procedure	Case 1: The Schiphol bottleneck area; 2 stations, 4 trains; Case 2: Overall Schiphol Dispatching Area, 5 stations, 27 trains per hour per direction, 15, 30, 45, 60 minutes time window.
[66]	Minimizing the total delay including the primary delay and the maximum consecutive delay	three greedy heuristics(FCFS, First leave first served (FLFS), AMCC), B&B [64] for reordering	The Schiphol bottleneck area; 5 stations, 27 trains per hour per direction.
[67]	Minimizing the total delay including the primary delay and the maximum consecutive delay	B&B [64] for reordering, local search for rerouting, and a speed adjustment procedure	-
[68]	Minimizing the total delay including the primary delay and the maximum consecutive delay	FCFS, B&B [64] for reordering, tabu search for rerouting, and a speed adjustment procedure	Case 1: Schiphol Dispatching Area; 5 stations, 27 trains per hour per direction; Case 2: Utrecht Dispatching Area; 1-hour time window, up to 80 trains.
[69]	Minimizing the maximum consecutive delay	B&B [64], FIFO, and an algorithm simulating the behavior of the dispatchers for reordering, and a speed adjustment procedure	Dutch railway network; 7 stations, 26 trains per hour in the station of Geldermalsen, up to 40 trains per hour in the station of Den Bosch.
[70]	Minimization of the maximum consecutive delay at each relevant point of the studied area	B&B [64] for reordering and a speed adjustment procedure[61]	Utrecht Dispatching Area; Up to 80 trains in a peak hour
[71]	Minimizing the Propagation of Delays	B&B and FCFS for reordering	A bottleneck of the Dutch railway network(Utrecht-Den Bosch), 191 block sections and 21 platforms, up to 40 trains are scheduled each hour.
[73]	Minimizing the maximum consecutive delay	B&B [64] for reordering and tabu search with different neighborhood structures fore rerouting	Utrecht Den Bosch railway; 1-hour cyclic time window; Up to 40 trains.
[74]	Minimizing the total delay including the primary delay and the maximum consecutive delay	FCFS, B&B [64] for reordering	The railway area around Utrecht Central; 1-hour cycle time window, 79 trains.
[75]	Minimizing the maximum consecutive delay	FCFS, B&B [64] for reordering, rerouting	Railway network in the South-East of the Netherlands; 1-hour time window, 12 trains.
[76]	Minimizing the total delay including the primary delay and the maximum consecutive delay	B&B [64] for reordering, tabu search for rerouting	Main station of Utrecht; 1-hour time window, up to 80 trains.
[77]	Minimizing train delays and missed connections	B&B [64] for reordering, two heuristics for selecting connections	Dutch railway network around the main station of Utrecht; 1-hour cyclic time window, up to 80 trains.
[78]	Minimizing the consecutive delay	B&B [64] for reordering in each local area, another B&B for coordinator problem	A large part of the railway network in the South-East of the Netherlands; 1-hour cyclic time window, up to 154 trains.
[79]	Minimizing the maximum secondary delay	B&B [64] for reordering	Case 1: between Utrecht and Den Bosch in the Netherlands; Case 2: Dutch national network, more than 700 passenger trains in one hour.
[72]	Minimizing consecutive delays	B&B [64], FCFS, and Automatische Rijweg Instelling (ARI) for reordering	Around the main station of Utrecht in the Netherlands; one peak hour of the 2008 timetable that schedules up to 80 trains.
[80]	Minimizing the total passenger delay	an iterative approach incorporating the computed wait depart decisions	A dense part of the railway network including Utrecht Central Station,46 stations,4 hour time horizon, 377 trains.
[81]	Minimizing the maximum consecutive delay	FIFO, AMCC, and B&B for rescheduling	Around the central station of Utrecht, 50 trains per hour per direction for the crossroads of the five main lines.
[82]	Minimizing train delays and travel times	Coordination heuristic	Complex railway network in the South-East of the Netherlands,more than 1200 block sections and station platforms, a cycle time of one hour and schedules around 150 trains.
[83]	Minimizing the maximum consecutive delay at each station	B&B and FIFO for reordering, TS for rerouting	The dispatching area of Campoleone-Nettuno, 10 stations, daily timetable has 42 trains.
[84]	Minimizing the total delay, the difference between the calculated train arrival time and the scheduled time	FCFS, FLFS, B&B, ArcGreedyHeuristics (AGH), Job Greedy Heuristic (JGH), Heuristic coordination, Exact coordination	A railway network in the South-East of the Netherlands, includes the major stations of Utrecht Central, Arnhem and Den Bosch,plus other 40 minor stations, more than 1000 block sections and 200 stopping locations.

TABLE XII
SUMMARY OF APPROACHES TO RESCHEDULING BASED ON THE DISCRETE EVENT MODEL

	Approaches	Objectives	Problem instances and sizes
[93]	Dynamic programming	Minimizing total weighted delay on the trains	Simulated data; 4 trains converge on a junction.
[94]	Greedy Travel Advance Strategy (TAS)	Minimizing energy costs	Simulated data, 12-hour time window, 36 trains.
[95]	Effective travel advance strategy based on the global information of the train	Minimizing total delay time of trains	Simulated data. Case 1: 24-hour time window, 36 trains; Case 2: 33 stations, 36 trains.
[97]	Two greedy heuristics	Minimizing the total time in system for passengers	Case 1: Synthetic Network; Case 2: Madrid Regional Railway Network (MRRN); Case 3: one of the most used lines in MRRN.
[98]	A bucket-based delay propagation algorithm	Minimizing propagation of train delays	-
[99], [100]	Quadratic programming	Minimizing the sum of deviations from the original schedule and the number of broken connections	Simulated data; 4 stations, 2 trains.
[101]	Quadratic programming	Minimizing the sum of the delay of all the trains and the cost related to the input events and other variants	Simulated data; 4 stations, 3 trains.
[102]	GA, SA, Tabu search	Minimizing the total weighted delay	-

discrete events and the state of each train at the given time. All the trains are controlled by the dynamic process through determining the optimal velocities, orders, and connections for optimizing different objectives. Ho *et al.* mentioned that the discrete event based model is more efficient than the discrete time based simulation model [93]. They later used three heuristic algorithms, which are genetic algorithms (GAs), simulated annealing (SA), and tabu search (TS), in the discrete event model to resolve conflicts in a reasonable computation time [102]. In [99], [100], the authors extended the model predictive control (MPC) framework from a discrete time model to a discrete event time model with soft and hard synchronization constraints for a railway network and used it to recover from the delays. In order to solve the MPC optimization problem effectively, it was recasted as an extended linear complementary problem (ELCP) [99], [100]. They also used the switching max-plus-linear systems as the discrete event system to model the railway system [101]. The summary of approaches to rescheduling based on the discrete event model is given in Table XII.

G. Simulation Model

The components of a railway network, such as railway infrastructure [103]–[105], train or passengers movements [103], [107], [108], dispatching process [106], etc., can be represented by a computer-based simulation model. The simulation model can not only simulate the real-time status of a railway system, but also forecast the future status of the railway system and have the ability to resolve conflicts. Therefore, the rescheduling approaches can be integrated into the simulation model to support real-time dispatching. The summary of approaches to rescheduling based on the simulation model is shown in Table XIII.

H. Other Models

Missikoff introduced a fast prototype of MINT (Manager of Integrated Networks of Train traffic), which was a decision support system for railway traffic control [110]. Barta *et al.* studied a method to forecast the delay propagation in railway networks by developing a Markov-chain based model [111], which was based on the examination of a large set of historical data and can discover the probability of absorbing or propagating delays. From the forecasted results, train dispatchers can evaluate the impact of a solution on the future state of the system and make better scheduling decisions.

From the view of the train driver recovery problem (TDRP) when major disruptions occur in railway networks, Rezanova *et al.* modeled the TDRP as a set partitioning problem [112]. Afeez proposed a method to model the railway system by storing the information of timetable, trains, railway network infrastructure, and events in xml files. In [114], some graph based models, such as a decision tree, a stage to stage transformation graph, an agent-based graph, and a decision arc model, were employed according to different solution approaches to minimize delays in railway networks. Albrecht *et al.* used a Possession Plans On Demand (PPOD) system to represent the railway network, including the network infrastructure, the way trains move in the network, and the train requirements [115].

The summary of different approaches to rescheduling based on the other models is given in Table XIV.

IV. DISCUSSION ON THE REVIEW RESULTS

A. Discussion on Problem Models and Problem Types

To understand the problem models better, a cross analysis of problem types in problem models is presented in Table XV. The problem types were mentioned in Section II. Fig. 3 shows the frequency of a problem model used per problem type and tells us very interesting results. The MILP model is not only studied by most publications but also used for most problem types, which reflects its popularity in this research area. From Fig. 3, we also find that different problem models have their own speciality in different problem types. For an AG model, it was extensively used in the conflict resolution rescheduling problem. The MILP model was studied much more in the disturbance recovery rescheduling problem and real-time rescheduling problem. The delay management rescheduling

TABLE XIII
SUMMARY OF APPROACHES TO RESCHEDULING BASED ON THE SIMULATION MODEL

	Approaches	Objectives	Problem instances and sizes
[103]	Velocity_Augmenting algorithm and deadlock-free algorithm	Minimizing the travel time of trains	Rail network from Downtown Los Angeles to the Eastern Inland Empire area; 141.5 freight trains and 101 passenger trains per day.
[104]	Repeatedly stepping forwards the simulation that has the lowest cost on the decision tree	Minimizing the sum of the deviations from the scheduled arrival time and the number of missed connections	A small region of track around a junction based on a real location in the U.K.; 30-minute time window, 5 trains.
[105]	Simulation approach	Optimizing the situation on punctuality, energy consumption and/or throughput	Railway station of Amsterdam Airport.
[106]	Banker's algorithm; TS	Minimizing the weighted overall trip time	Simulation data; Up to 5 trains.
[107]	Program Evaluation and Review Technique (PERT), SA	Minimizing Passengers' Dissatisfaction	A line in Tokyo urban area; 19 stations, one-day time window, 564 trains.
[108]	PERT, TS	Minimizing Passengers' Dissatisfaction	Real world timetable; 41 stations, 40 trains, a Cyclic time window.
[109]	PERT	Minimizing passenger inconvenience	-
[120]	rerouting or retiming by simulation	Minimizing the total amount of delay experienced by all trains in the network	a critical bottleneck (Lucerne) in the Swiss rail network, 30 trains per hour, 10 platforms in a terminal station

TABLE XIV
SUMMARY OF APPROACHES TO RESCHEDULING BASED ON THE OTHER MODELS

	Approaches	Objectives	Problem instances and sizes
[110]	Hill climbing, A*, and mixed of them	A combination of the sum of the weights of the solutions already selected and the number and weight of the solutions required by the remaining conflicts, before reaching the goal	South of Rome; 10 trains, 13 stations.
[112]	Dynamic column generation and B&B	Minimizing the number of modifications from the original schedule forces the disruption neighborhood to be as small as possible	Historical data from one day of S-tog; Up to 33 trains running within a time period of 5 min from the recovery start time.
[113]	Greedy heuristics approach, the best-first search heuristic approach	Minimizing the delay of all the delayed trains	Case 1: 4 stations, 7 trains; Case 2: 6 stations, 5 trains; Case 3: 4 stations, 4 trains.
[114]	FCFS, Decision Tree Based Elimination (DTBE), TS, ACO, GA, Dynamic Programming (DP), Brute Force (BF)	Minimizing the total delay cost	Case 1: A layout based on the North Stafford and Stenson Junctions on the Derby to Birmingham line in the UK, 12 trains approaching one junction area; Case 2: Multi-junction case study on the Derby-Birmingham, 31 trains, 3 junctions.
[115]	Problem Space Search	Minimizing sum of the individual train delays plus any maintenance delays	On the North Coast Line in Queensland; 50 trains.

problem seems to be modelled more by the IP and discrete event models.

B. Discussion on Solution Approaches

Branch & bound (B&B), heuristic approaches, meta-heuristic approaches (including GAs, SA, TS, Ant Colony Optimization (ACO), Evolutionary Algorithms (EAs)), standard solvers (including CPLEX, GLPK, etc.), and some other kinds of approaches have been studied in the literature. Table XVI presents the cross analysis of solution approaches and problem models mentioned above. The frequency of each solution approach used in each problem model is shown in Fig. 4.

A heuristic is an experience-based technique for the algorithms to find the solutions more quickly when the exhaustive search is impractical. Heuristic algorithms do not guarantee to obtain the optimal solution but find a near optimal solution. As rescheduling in railway networks is an NP-hard problem, exact mathematical approaches are not capable of finding the solutions within a limited time. Therefore, researchers have developed various heuristic approaches incorporating different problem models for rescheduling in railway networks, in order to get good enough solutions in a reasonable amount of time. From Fig. 4, it is obvious that heuristic algorithms are not only the most frequently used but also the most widely used approaches among all solution approaches, which shows their practical advantages in balancing the solution quality and computation time.

The B&B approach is an exhaustive algorithm that explores all possible sequences of trains. It is effective to solve small rescheduling problems and obtain the optimal solutions. However, the computation time will increase greatly with the increasing problem scale. Therefore, researchers usually used the B&B approach in a limited time to obtain a near-optimal solution and sometimes took the near-optimal solution as an initial solution to other algorithms. In the literature, the B&B approach was studied in the IP, MILP, CP and AG models, especially in the AG model as shown in Fig. 4.

Meta-heuristic approaches can solve a wide range of different problems by an iterative process without knowing the

TABLE XV
CROSS ANALYSIS OF PROBLEM TYPES IN PROBLEM MODELS

	IP	MILP	CP	AG	Discrete event model	Simulation model	Other models	*Total*
CDR	-	[38]	[60]–[62]	[63]–[70], [73]–[79], [83]	[93]	-	[110] [114]	22
Delay management	[13]–[19]	[45]	-	[80]	[95], [98]–[102]	[104], [108]	[112]	18
Disturbance recovery	-	[29]–[36], [51]–[53]	-	[71], [72], [81], [82], [84]	-	-	-	16
Real-time rescheduling	[26]	[39]–[43], [46], [50], [54], [55]	[57]	-	-	[120]	-	12
Train dispatching	-	[47], [48]	-	-	[94]	[103] [105] [106]	[113]	7
Crew/vehicle/timetable rescheduling	[23]–[25]	[37], [44]	[59]	-	[97]	-	-	7
Disruption recovery	[20], [22]	-	-	-	-	[107] [109]	[115]	5
Total	13	26	5	22	8	7	5	87

In the table, the symbol '-' means that there are no papers related to the problem type and problem model.

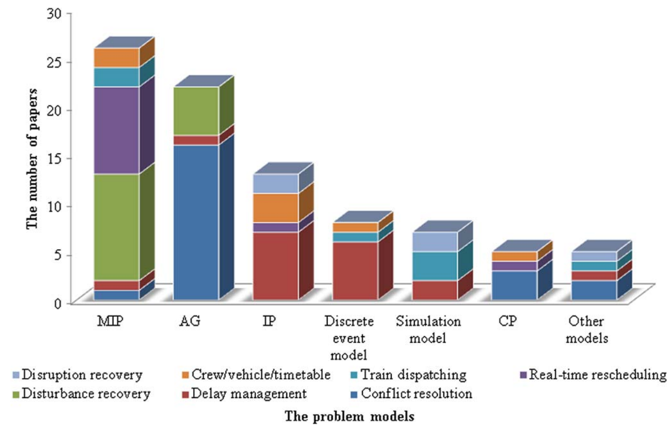

Fig. 3. The frequency of a problem model used per problem type.

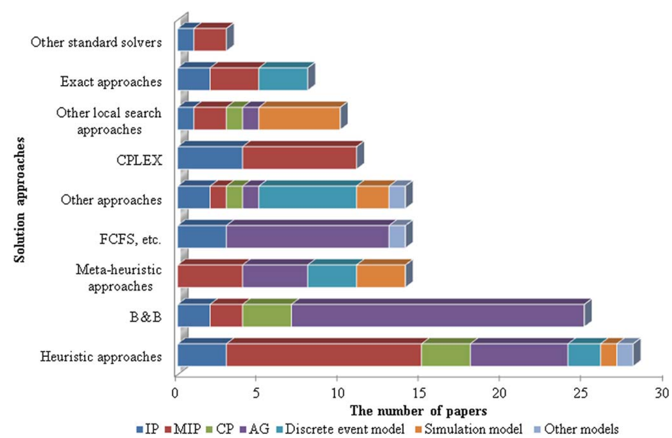

Fig. 4. The frequency of solution approaches used per problem model.

exact problem structures and obtain very good near-optimal solutions if enough iterations are given. There are 14 reviewed papers that used meta-heuristic approaches in four kinds of problem models for rescheduling in railway networks. Half of the 14 reviewed papers were published after year 2010, which shows that more researchers have been following meta-heuristic approaches in this research area now. As rescheduling in railway networks is time-critical, meta-heuristic approaches are only permitted to run in limited iterations in order to meet the time requirements. In [46], an EA was used to quickly get an initial solution within the given iterations and then it was fed to CPLEX in order to solve the problem efficiently. A better initial solution found by the meta-heuristic approaches is helpful for the solution procedure. In [107], the authors used the Program Evaluation and Review Technique (PERT) technique to determine the arrival and departure times of trains and then used SA to quickly determine other variables in the reduced solution space. Among the literature, meta-heuristic approaches were mainly used to determine the binary variables, such as the order of trains, cancellation of trains, and routes of trains.

First-come-first-served (FCFS) is a well-known dispatching rule and widely used in railway control centers as it is easy to understand and utilize. In the FCFS approach, trains are rescheduled according to their actual order of arrival. The FCFS approach can response to a disturbance quickly but its

TABLE XVI
CROSS ANALYSIS OF SOLUTION APPROACHES IN PROBLEM MODELS

	IP	MILP	CP	AG	Discrete event model	Simulation models	Other models	*Total*
Heuristic approaches (Greedy, AMCC, etc.)	[17], [19], [23]	[29], [30], [32]–[35], [37], [38], [45], [47], [48], [55]	[59], [61], [63]	[65], [66], [77], [81], [82], [84]	[94] [97]	[103]	[113]	28
B&B	[15], [20]	[39], [46]	[57], [61], [62]	[64]–[70], [72]–[79], [81], [83], [84]	-	-	-	25
Meta-heuristic approaches (SA, TS, GA, EA, ACO)	-	[31], [40], [41], [46]	-	[68], [73], [76], [83]	[102], [114], [115]	[106]–[108]	-	14
FCFS, FRFS, FIFO, FOFI, FSFS	[14]–[16]	-	-	[65], [66], [68], [69], [72], [74], [75], [81], [83], [84]	-	-	[114]	14
Other approaches	[13], [26]	[51]	[60]	[80]	[93], [95], [98]–[101]	[105], [106]	[114]	14
Standard solver (CPLEX)	[17], [18], [22], [24]	[31], [43], [44], [46]–[48], [54]	-	-	-	-	-	11
Other local search approaches	[23]	[42], [53]	[62]	[67]	-	[104], [107]–[110]	-	10
Exact approaches*	[18], [25]	[36], [50], [53]	-	-	-	-	[112]	6
Other standard solvers**	[13]	[43], [52]	-	-	-	-	-	3

*Exact approaches refer to Decomposition algorithm [50],Column generation [112],SAPI [36],Lagrangian relaxtion method [25],Dijkstra's algorithm [18], and Right-shift [53].**Other standard solvers include GLPK, CBC, COIN-OR, DIP, SYMPHONY.
The symbol '-' means that there are no papers related to the solution approach and problem model.

solutions are usually suboptimal. Several similar dispatching rules, such as first-in-first-out (FIFO), first-out-first-in (FOFI), first rescheduled first served (FRFS), first scheduled first served (FSFS), etc., were also tried for the rescheduling problem. As CPLEX is a standard solver for linear programming problems, it is only used in the IP and MILP models as shown in Fig. 4.

It is well-known that the tradeoff between the computational complexity and the solution quality is inevitable for rescheduling. Although several approaches have been studied, it is still very difficult for only one approach to meet the tradeoff requirement satisfactorily. A common strategy to meet the demand is to reduce the solution space by various measures to speed up the computation. The measures include fixing the order of trains [14], [16], [29], [30], fixing variables [22], [36], [50], [53], reducing constraints [20], fixing the routing [48], etc. An interesting research trend for the future is that two or more approaches can be integrated to solve the problem by considering their own advantages and characteristics [121], [122]. The solution process can be divided into two or more stages. In the first stage, one approach is used to reduce the search space or obtain an approximately solution in a short time or determine only part of the variables. During the later stages, other approaches are used to obtain improved and refined solutions or other parts of the variables. In [31], an iterative two-level process was proposed with the start and end times of each train optimized by CPLEX in the first level, and the order of trains on blocks determined by SA and TS in the second level. Similar to [31], two consecutive stages were employed to determine the departure/arrival times of each train and the orders/routes of trains respectively in [107]. In [63], [65], [67]–[70], [73], reordering and rerouting of trains were usually calculated by different approaches in different stages and often followed by a speed regulation procedure to compute the optimal speed profile. Parallel computing techniques and greedy algorithms were also employed to speed up the solution procedure [34].

C. *Discussion on Problem Instances and Sizes*

We have reported the problem instance and size in Tables V, VII, VIII, XI–XIV. There are two types of problem instances that have been studied in the literature, which come from the real-world railway networks and simulated instances. Fig. 5 presents the percentage of different problem instances in the literature. It is clear that the researchers were in favor of real-world railway networks as the problem instances. The problem instances from Europe railway networks have the biggest proportion, with the Netherlands railway networks dominating the studies. This situation is not surprising as the researchers pointed out that the coverage rate of the Dutch rail network is high [105].

As the problem size is concerned, the number of trains and stations in the problem instances is always considered in the literature, which can reflect the problem scale. The number of platforms, blocks, segments, and junctions are also usually given to describe the problem instance. The problem size is quite different across the literature. A small problem size can be found in [65], where 2 stations and 4 trains were considered.

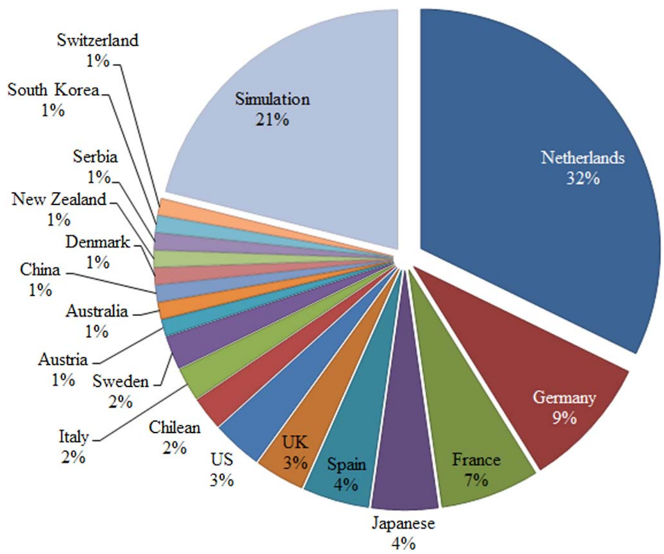

Fig. 5. Percentage of different problem instances in the literature.

The Dutch national railway network, which is a large-scale problem instance with 298 stations and over 700 passenger trains operating during peak hours, was studied in [79].

D. Discussion on Problem Models and Solution Approaches

From the experimental results reported in the literature, various new solution approaches and different problem models for rescheduling problems in railway networks have shown their abilities in the laboratory condition. The problem types, problem instances and sizes studied in the literature tell us that the real-world railway networks are much more complicated. Therefore, among the literature there were very few new solution approaches for rescheduling that were actually used in the traffic management systems (TMS) [37], [98], [105], [118], [123]. One possible reason might be that the solution approach could not manage the diverse situations arising in the real-world railway networks.

With the increasing of the problem scale for rescheduling, the search space grows exponentially. The balance between the computation time and solution accuracy becomes more crucial. On one hand, by reducing the solution space to speed up the computation would still be a good choice. On the other hand, the model's precision will inevitably decrease by the reduced solution space and thus influence the solution quality. Therefore, the solution approaches that can deal with large-scale optimization problems would be helpful to tackle this situation. Some novel EAs have been proposed to solve the large scale global optimization problems without reducing the search space. The performance of these EAs have been demonstrated on 1000, 2000 and 5000 dimension functions [124], [125]. It would be interesting in the future to investigate similar approaches to the rescheduling problem.

In terms of the objectives of rescheduling in railway networks, the interests of two parties, which are the railway companies and the passengers, should both be considered but are often conflicting. Few literature has taken two or more objectives into their consideration. One of the reasons might be that it is not easy to define a multi-objective function and the single objective problem is already very hard. In the literature, researchers usually combined different criteria into one objective by the method of weighting since it is easier to solve a single objective problem than a multi-objective one. However, the value of each weight can be hard to determine in practice. Considering the rescheduling problem in railway networks with separate multiple objectives may be more beneficial and natural than the weighted sum approach. As far as potential multi-objective solution approaches are concerned, some recent multi-objective EAs could be used [126]–[128]. It should be noted that EAs themselves have their own limitations. Their performance may rely on their parameters. Selecting the best EA parameters may be a challenge task. Based on the review results, we think the integration of EAs with other approaches may be a promising way to solve the rescheduling problem in railway networks when we face large scale or multi-objective optimization problems.

Excluding the publications produced by the same research groups, the performance comparison among different solution approaches based on various problem models is hard to find in the literature, except for [38]. Only solutions by CPLEX or FCFS are often compared to approaches proposed by researchers. The main reason is the lack of benchmark problem instances for railway networks. This was already criticised by [2], but the situation has not been improved since then. Different problem models used in the literature make the situation even more challenging. The representation of the infrastructure, preconditions, constraints, and objective functions are usually different among different papers, making comparisons between different approaches difficult, if not impossible.

E. Discussion on Objective Functions

In Tables V, VII, VIII, XI–XIV, the objectives used in the literature are presented. The various kinds of objectives can inform us about the rescheduling tactics, which reflect the difference among these objectives. As the train punctuality is an important indicator in railway networks, most of the authors defined the minimization of delays as the objective function. However, definitions for the minimization of delays are diverse, e.g., minimizing the total delay including the primary delay and the maximum consecutive delay [66], minimizing the sum of all delays over all customers [13], minimizing the total final delay of the traffic system [31], minimizing passenger delays [59], etc. Some definitions for delay deviation were also used, such as the deviation between the origin schedule and the new schedule [20], the total variance in delays [55], and the overall trip time [106].

Besides considering delays as the objective, the cost is often taken into account for rescheduling, such as the sum of all the flow costs for crew or vehicle [25], the total rescheduling cost [36], [45], the energy cost [94], the cost for missing or breaking connections [15], [40], switching train orders [40], unplanned stops, changing of tracks and platforms. A few researchers considered the rescheduling problem from the aspect of passengers and defined the minimization of passengers' dissatisfaction as the objective [26], [107]–[109].

TABLE XVII
FREQUENCY OF VARIOUS OBJECTIVES USED PER PROBLEM TYPE

Problem type	Objectives						
	A	B	C	D	E	F	G
CDR	8	10	0	0	1	1	2
Delay management	0	7	1	3	6	1	1
Disturbance recovery	3	11	0	0	0	4	0
Real-time rescheduling	0	6	1	0	0	4	0
Train dispatching	0	4	0	0	0	1	1
Crew/vehicle/timetable rescheduling	0	1	0	2	0	4	1
Disruption recovery	0	2	2	0	0	0	1
Total	11	41	4	5	7	15	6

A. Minimizing the maximum consecutive delay
B. Minimizing the total delay of trains
C. Minimizing the passengers' dissatisfaction
D. Minimizing the delay of passengers
E. Minimizing the delay & the number of broken or missing connections
F. Minimizing the total costs or costs related
G. Not classified

Table XVII presents the frequency of various objectives used in each problem type. As can be seen, the total delay of trains was the most used objective and was used in all problem types. The total cost and cost related objectives are the second most used objective. For the problem type of CDR, the main objective used in the literature is the minimization of the maximum consecutive delay and the total delay of trains. According to Table XVII, some papers not only considered the delay as the objective, but also took account of the number of broken or missing connections, which shows that two objectives were studied simultaneously. In [77], Corman *et al.* designed the multi-objective CDR problem instead of using the single-objective and proposed heuristic algorithms to find the Pareto front of non-dominated solutions.

V. CONCLUSIONS AND FUTURE WORK

Rescheduling in railway networks has received much attention in recent years, including the problem models and solution approaches, which are extensively reviewed in this paper. The details of IP, MILP, and AG models are summarized in this paper according to their characteristics, which can help researchers to understand these models and use them appropriately. The main ideas of solution approaches are presented. The advantages and disadvantages of frequently used solution approaches are discussed. An attempt is made to analyse the relationship between problem models and problem types, and the relationship between solution approaches and problem models. The problem instances and sizes are also analysed. The objective functions are reviewed in detail too.

Some major observations can be made from our review. First, there is a diverse range of different problem types and models. As a result, it is very difficult, if not impossible, to evaluate and compare different solution approaches. This is clearly a very useful future research direction. For example, a suite of benchmark problem instances that enable researchers to evaluate and compare their solution approaches would really help to move the research forward.

Second, scalability continues to be a challenge. We need to develop solution approaches that can deal with large scale problems, covering a large number of trains, stations, block sections, and various constraints. Hybrid approaches combining exact and heuristic methods appear to be a promising future direction.

Third, multiple criteria were often discussed but not modelled and solved satisfactorily. There have been few papers on true multi-objective approaches to rescheduling, trying to find a good approximation to the Pareto front. Some solution approaches from the multi-objective EAs could be investigated for their potential adaptation to rescheduling in railway networks.

Fourth, although current research results showed the effectiveness of the proposed problem models and solution approaches based on the computational experiments, few of them mentioned that the research results were actually used in practice in train dispatching systems. For the future research, we would like to see the new problem models and solutions approaches that can be adopted in train dispatching systems.

Fifth, for the real-time rescheduling problem type in railway networks, it is more likely to happen in practice. However, the reason that causes disturbances is often uncertain and unforeseen. Therefore, solution approaches arising from meta-heuristics for solving the problems in dynamic and uncertain environments would be a good choice for the real-time rescheduling problem as a future research.

Finally, there has been little work on combining search algorithms with knowledge-based approaches. It would be interesting to explore the combination of human expertise with search algorithms as one way to tackle the issue of a huge solution space.

REFERENCES

[1] S. Narayanaswami and N. Rangaraj, "Scheduling and rescheduling of railway operations: A review and expository analysis," *Technol. Oper. Manage.*, vol. 2, no. 2, pp. 102–122, Dec. 2011.

[2] J. Törnquist, "Computer-based decision support for railway traffic scheduling and dispatching: A review of models and algorithms," in *Proc. 5th Workshop Algorithmic Methods Models Optim. Railways*, 2006, p. 659.

[3] G. E. Vieira, J. W. Herrmann, and E. Lin, "Rescheduling manufacturing systems: A framework of strategies, policies, and methods," *J. Sched.*, vol. 6, no. 1, pp. 39–62, Jan. 2003.

[4] M. Carey, "Extending a train pathing model from one-way to two-way track," *Transp. Res. B, Methodol.*, vol. 28, no. 5, pp. 395–400, Oct. 1994.

[5] M. Carey, "A model and strategy for train pathing with choice of lines, platforms, and routes," *Transp. Res. B, Methodol.*, vol. 28, no. 5, pp. 333–353, Oct. 1994.

[6] M. Carey and D. Lockwood, "A model, algorithms and strategy for train pathing," *J. Oper. Res. Soc.*, vol. 46, no. 8, pp. 988–1005, Aug. 1995.

[7] R. Acuna-Agost, P. Michelon, D. Feillet, and S. Gueye, "Constraint programming and mixed integer linear programming for rescheduling trains under disrupted operations," in *Proc. 6th Int. Conf. Integr. AI OR Tech. Constraint Programm. Combinatorial Optim. Probl.*, 2009, vol. 5547, Lecture Notes in Computer Science, pp. 312–313.

[8] D. Pacciarelli, "Introduction and classification of existing rescheduling literature," in *Proc. 5th Int. Semin. Rail Oper. Modeling Anal. Rail-Copenhagen*, Lyngby, Denmark, Course Lecture, 2013, pp. 1–48.

[9] V. Cacchiani *et al.*, "An overview of recovery models and algorithms for real-time railway rescheduling," *Transp. Res. B, Methodol.*, vol. 63, pp. 15–37, May 2014.

[10] Z. Alwadood, A. Shuib, and N. A. Hamid, "Mathematical rescheduling models for railway services," *Int. J. Math., Comput., Phys. Quantum Eng.*, vol. 7, no. 8, pp. 798–803, 2013.

[11] Z. Alwadood, A. Shuib, and N. A. Hamid, "A review on quantitative models in railway rescheduling," *Int. J. Sci. Eng. Res.*, vol. 3, no. 6, pp. 1–7, Jun. 2012.

[12] F. Corman and L. Meng, "A review of online dynamic models and algorithms for railway traffic management," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 3, pp. 1274–1284, Jun. 2014.

[13] A. Schöbel, "Integer programming approaches for solving the delay management problem," in *Proc. 4th Int. Workshop Algorithmic Methods Railway Optim.*, 2007, vol. 4359, Lecture Notes in Computer Science, pp. 145–170.

[14] M. Schachtebeck and A. Schöbel, "IP-based techniques for delay management with priority decisions," in *Proc. 8th Workshop Algorithmic ATMOS*, Karlsruhe, Germany, vol. 9, 2008, pp. 1–16.

[15] A. Schöbel, "Capacity constraints in delay management," *Public Transp.*, vol. 1, no. 2, pp. 135–154, Jun. 2009.

[16] M. Schachtebeck and A. Schöbel, "To wait or not to wait and who goes first? Delay management with priority decisions," *Transp. Sci.*, vol. 44, no. 3, pp. 307–321, 2010.

[17] T. Dollevoet, M. Schmidt, and A. Schöbel, "Delay management including capacities of stations," in *Proc. 11th Workshop Algorithmic Approaches Transp. Model., Optim., Syst.*, Wadern, Germany, 2011, vol. 20, pp. 88–99.

[18] T. Dollevoet, D. Huisman, M. Schmidt, and A. Schöbel, "Delay management with rerouting of passengers," *Transp. Sci.*, vol. 46, no. 1, pp. 74–89, Feb. 2012.

[19] T. Dollevoet and D. Huisman, "Fast heuristics for delay management with passenger rerouting," Erasmus Univ. Rotterdam, Rotterdam, The Netherlands, Tech. Rep. Econometric Inst. EI2011-35, Oct. 2011.

[20] C. G. Walker, J. N. Snowdon, and D. M. Ryan, "Simultaneous disruption recovery of a train timetable and crew roster in real time," *Comput. Oper. Res.*, vol. 32, no. 8, pp. 2077–2094, Aug. 2005.

[21] K. Nachtigall, "Periodic network optimization with different arc frequencies," *Discr. Appl. Math.*, vol. 69, no. 1/2, pp. 1–17, Aug. 1996.

[22] S. P. Fekete, A. M. L. Kröller, and M. Pfetsch, "Disruption management with rescheduling of trips and vehicle circulations," in *Proc. ASME/ASCE/IEEE Joint Rail Conf.*, 2011, pp. 395–404.

[23] T. Sato, S. Sakikawa, T. Morita, N. Ueki, and T. Muratay, "Crew and vehicle rescheduling based on a network flow model and its application to a railway train operation," *IAENG Int. J. Appl. Math.*, vol. 39, no. 3, pp. 142–150, Sep. 2009.

[24] K. Sato and N. Fukumura, "An algorithm for freight train driver rescheduling in disruption situations," *Quart. Rep. RTRI*, vol. 51, no. 2, pp. 72–76, 2010.

[25] T. Sato, T. Tomiyama, T. Morita, and T. Murata, "A Lagrangian relaxation method for crew and vehicle rescheduling of railway passenger transportation and its application," *IEEJ Trans. Electron., Inf. Syst.*, vol. 132, no. 2, pp. 260–268, 2012.

[26] G. Caimi, M. Fuchsberger, M. Laumanns, and M. Lüthi, "A model predictive control approach for discrete-time rescheduling in complex central railway station areas," *Comput. Oper. Res.*, vol. 39, no. 11, pp. 2578–2593, Nov. 2012.

[27] X. Cai and C. J. Goh, "A fast heuristic for the train scheduling problem," *Comput. Oper. Res.*, vol. 21, no. 5, pp. 499–510, May 1994.

[28] X. Cai, C. J. Goh, and A. I. Mees, "Greedy heuristics for rapid scheduling of trains on a single track," *IIE Trans.*, vol. 30, no. 5, pp. 481–493, 1998.

[29] J. Törnquist, "Railway traffic disturbance management—An experimental analysis of disturbance complexity, management objectives and limitations in planning horizon," *Transp. Res. A, Policy Pract.*, vol. 41, no. 3, pp. 249–266, Mar. 2007.

[30] J. Törnquist and J. A. Persson, "N-tracked railway traffic re-scheduling during disturbances," *Transp. Res. B, Methodol.*, vol. 41, no. 3, pp. 342–362, Mar. 2007.

[31] J. Törnquist and J. A. Persson, "Train traffic deviation handling using tabu search and simulated annealing," in *Proc. 38th Annu. Hawaii Int. Conf. Syst. Sci.*, 2005, p. 73a.

[32] J. Törnquist, "Greedy algorithm for railway traffic re-scheduling during disturbances: A Swedish case," *IET Intell. Transp. Syst.*, vol. 4, no. 4, pp. 375–386, Dec. 2010.

[33] J. Törnquist, "Design of an effective algorithm for fast response to the re-scheduling of railway traffic during disturbances," *Transp. Res. C, Emerging Technol.*, vol. 20, no. 1, pp. 62–78, Feb. 2012.

[34] H. Grahn and J. Törnquist, "A parallel rescheduling algorithm for railway traffic disturbance management—Initial results," in *Proc. 2nd Int. Conf. Models Technol. Intell. Transp. Syst.*, 2011, pp. 1–4.

[35] S. Iqbal, H. Grahn, and J. Törnquist, "A comparative evaluation of rescheduling strategies for train dispatching during disturbances," in *Proc. 13th Int. Conf. Des. COMPRAIL Eng.*, 2012, pp. 567–579.

[36] R. Acuna-Agost, P. Michelon, D. Feillet, and S. Gueye, "SAPI: Statistical analysis of propagation of incidents. A new approach for rescheduling trains after disruptions," *Eur. J. Oper. Res.*, vol. 215, no. 1, pp. 227–243, Nov. 2011.

[37] B. Adenso-Díaz, M. O. González, and P. González-Torre, "On-line timetable re-scheduling in regional train services," *Transp. Res. B, Methodol.*, vol. 33, no. 6, pp. 387–398, Aug. 1999.

[38] Y.-H. Min, M.-J. Park, S.-P. Hong, and S.-H. Hong, "An appraisal of a column-generation-based algorithm for centralized train-conflict resolution on a metropolitan railway network," *Transp. Res. B, Methodol.*, vol. 45, no. 2, pp. 409–429, Feb. 2011.

[39] M. Dessouky, Q. Lu, J. Zhao, and R. Leachman, "An exact solution procedure to determine the optimal dispatching times for complex rail networks," *IIE Trans.*, vol. 38, no. 2, pp. 141–152, Feb. 2006.

[40] T. J. J. van den Boom and B. De Schutter, "Dynamic railway network management using switching max-plus-linear models," in *Proc. 11th IFAC Symp. Control Transp. Syst.*, 2006, pp. 343–348.

[41] T. J. J. van den Boom and B. De Schutter, "On a model predictive control algorithm for dynamic railway network management," in *Proc. 2nd Int. Semin. RailHannover Oper. Model. Anal.*, 2007, pp. 1–15.

[42] T. J. J. van den Boom, N. Weiss, W. Leune, R. M. P. Goverde, and B. De Schutter, "A permutation-based algorithm to optimally reschedule trains in a railway traffic network," in *Proc. 18th IFAC World Congr.*, 2011, pp. 9537–9542.

[43] J. Rudan, B. Kersbergen, T. van den Boom, and K. Hangos, "Performance analysis of MILP based model predictive control algorithms for dynamic railway scheduling," in *Proc. Eur. Control Conf.*, 2013, pp. 4562–4567.

[44] L. Wang, Y. Qin, J. Xu, and L. Jia, "A fuzzy optimization model for high-speed railway timetable rescheduling," *Discr. Dyn. Nat. Soc.*, vol. 2012, 2012, Art. ID. 827 073.

[45] N. Kliewer and L. Suhl, "A note on the online nature of the railway delay management problem," *Networks*, vol. 57, no. 1, pp. 28–37, Jan. 2011.

[46] L. Gély, G. Dessagne, and C. Lérin, "Modelling train rescheduling with optimization and operational research techniques—results and applications at SNCF," in *Proc. World Congr. Railway Res.*, Montreal QC, Canada, 2006.

[47] M. Boccia, C. Mannino, and I. Vasiliev, "Solving the dispatching problem on multi-track territories by mixed integer linear programming," in *Proc. RAS Competition/INFORMS Meet.*, 2012, pp. 1–16.

[48] M. Boccia, C. Mannino, and I. Vasilyev, "The dispatching problem on multitrack territories: Heuristic approaches based on mixed integer linear programming," *Networks*, vol. 62, no. 4, pp. 315–326, Dec. 2013.

[49] S. Mu and M. Dessouky, "Scheduling freight trains traveling on complex networks," *Transp. Res. B, Methodol.*, vol. 45, no. 7, pp. 1103–1123, Aug. 2011.

[50] C. Yan and L. Yang, "Mixed-integer programming based approaches for the movement planner problem: Model, heuristics and decomposition," in *Proc. RAS Problem Solving Competition*, 2012, pp. 1–14.

[51] R. M. Lusby, J. Larsen, M. Ehrgott, and D. M. Ryan, "A set packing inspired method for real-time junction train routing," *Comput. Oper. Res.*, vol. 40, no. 3, pp. 713–724, Mar. 2013.

[52] S. Narayanaswami and N. Rangaraj, "Modelling disruptions and resolving conflicts optimally in a railway schedule," *Comput. Ind. Eng.*, vol. 64, no. 1, pp. 469–481, Jan. 2013.

[53] R. Acuna-Agost, P. Michelon, D. Feillet, and S. Gueye, "A MIP-based local search method for the railway rescheduling problem," *Networks*, vol. 57, no. 1, pp. 69–86, Jan. 2011.

[54] P. Pellegrini, G. Marlière, and J. Rodriguez, "Optimal train routing and scheduling for managing traffic perturbations in complex junctions," *Transp. Res. B, Methodol.*, vol. 59, pp. 58–80, Jan. 2014.

[55] D. R. Kraay and P. T. Harker, "Real-time scheduling of freight railroads," *Transp. Res. B, Methodol.*, vol. 29, no. 3, pp. 213–229, Jun. 1995.

[56] R. Acuna-Agost, "Mathematical modeling and methods for rescheduling trains under disrupted operations," Ph.D. dissertation, Lab. Inf. d'Avignon, Univ. d'Avignon, Avignon, France, 2010.

[57] J. Rodriguez, "A constraint programming model for real-time train scheduling at junctions," *Transp. Res. B, Methodol.*, vol. 41, no. 2, pp. 231–245, Feb. 2007.

[58] J. Rodriquez and L. Kermad, "Constraint programming for real-time train circulation management problems in railway nodes," in *Proc. 6th Int. Conf. Compute. Aided Des., Manuf. Oper. Railway Adv. Mass Transit Syst.—Comput. Railways VI*, 1998, pp. 599–606.

[59] C. K. Chiu, C. M. Chou, J. H. M. Lee, H. F. Leung, and Y. W. Leung, "A constraint-based interactive train rescheduling tool," *Constraints*, vol. 7, no. 2, pp. 167–198, Apr. 2002.

[60] E. Oliveira and B. M. Smith, "A job-shop scheduling model for the single-track railway scheduling problem," in *Research Report Series*, no. 21. Leeds, U.K.: University of Leeds School of Computer Studies, 2000.

[61] E. Oliveira and B. M. Smith, "A hybrid constraint-based method for single-track railway scheduling problem," Univ. Leeds, Leeds, U.K., Tech. Rep., 2001.

[62] E. Oliveira and B. M. Smith, "A combined constraint-based search method for single-track railway scheduling problem," in *Proc. 10th EPIA Portuguese Conf. Artif. Intell.*, 2001, vol. 2258, Lecture Notes in Computer Science, pp. 371–378.

[63] M. Mazzarello and E. Ottaviani, "A traffic management system for real-time traffic optimisation in railways," *Transp. Res. B, Methodol.*, vol. 41, no. 2, pp. 246–274, Feb. 2007.

[64] A. D'Ariano, D. Pacciarelli, and M. Pranzo, "A branch and bound algorithm for scheduling trains in a railway network," *Eur. J. Oper. Res.*, vol. 183, no. 2, pp. 643–657, Dec. 2007.

[65] A. D'Ariano, M. Pranzo, and I. A. Hansen, "Conflict resolution and train speed coordination for solving real-time timetable perturbations," *IEEE Trans. Intell. Transp. Syst.*, vol. 8, no. 2, pp. 208–222, Jun. 2007.

[66] A. D'Ariano, D. Pacciarelli, and M. Pranzo, "Assessment of flexible timetables in real-time traffic management of a railway bottleneck," *Transp. Res. C, Emerging Technol.*, vol. 16, no. 2, pp. 232–245, Jun. 2008.

[67] A. D'Ariano, F. Corman, D. Pacciarelli, and M. Pranzo, "Reordering and local rerouting strategies to manage train traffic in real time," *Transp. Sci.*, vol. 42, no. 4, pp. 405–419, Nov. 2008.

[68] A. D'Ariano, "Innovative decision support system for railway traffic control," *IEEE Intell. Transp. Syst. Mag.*, vol. 1, no. 4, pp. 8–16, Winter 2009.

[69] F. Corman, A. D'Ariano, D. Pacciarelli, and M. Pranzo, "Evaluation of green wave policy in real-time railway traffic management," *Transp. Res. C, Emerging Technol.*, vol. 17, no. 6, pp. 607–616, Dec. 2009.

[70] F. Corman, R. M. P. Goverde, and A. D'Ariano, "Rescheduling dense train traffic over complex station interlocking areas," *Robust and Online Large-Scale Optimization*, vol. 5868, ser. Lecture Notes in Computer Science. Berlin, Germany: Springer-Verlag, 2009, ch. 16, pp. 369–386.

[71] A. D'Ariano and M. Pranzo, "An advanced real-time train dispatching system for minimizing the propagation of delays in a dispatching area under severe disturbances," *Netw. Spatial Econ.*, vol. 9, no. 1, pp. 63–84, Mar. 2009.

[72] F. Corman, A. D'Ariano, D. Pacciarelli, and M. Pranzo, "Centralized versus distributed systems to reschedule trains in two dispatching areas," *Public Transp.*, vol. 2, no. 3, pp. 219–247, Aug. 2010.

[73] F. Corman, A. D'Ariano, D. Pacciarelli, and M. Pranzo, "A tabu search algorithm for rerouting trains during rail operations," *Transp. Res. B, Methodol.*, vol. 44, no. 1, pp. 175–192, Jan. 2010.

[74] F. Corman, A. D'Ariano, I. A. Hansen, and D. Pacciarelli, "Optimal multi-class rescheduling of railway traffic," *J. Rail Transp. Planning Manage.*, vol. 1, no. 1, pp. 14–24, Nov. 2011.

[75] F. Corman, A. D'Ariano, I. A. Hansen, D. Pacciarelli, and M. Pranzo, "Dispatching trains during seriously disrupted traffic situations," in *Proc. IEEE ICNSC*, 2011, pp. 323–328.

[76] F. Corman, A. D'Ariano, M. Pranzo, and I. A. Hansen, "Effectiveness of dynamic reordering and rerouting of trains in a complicated and densely occupied station area," *Transp. Planning Technol.*, vol. 34, no. 4, pp. 341–362, Jun. 2011.

[77] F. Corman, A. D'Ariano, D. Pacciarelli, and M. Pranzo, "Bi-objective conflict detection and resolution in railway traffic management," *Transp. Res. C, Emerging Technol.*, vol. 20, no. 1, pp. 79–94, Feb. 2012.

[78] F. Corman, A. D'Ariano, I. A. Hansen, and D. Pacciarelli, "Optimal inter-area coordination of train rescheduling decisions," *Transp. Res. E, Logist. Transp. Rev.*, vol. 48, no. 1, pp. 71–88, Jan. 2012.

[79] P. Kecman, F. Corman, A. D'Ariano, and R. M. P. Goverde, "Rescheduling models for railway traffic management in large-scale networks," *Public Transp.*, vol. 5, no. 1/2, pp. 95–123, Sep. 2013.

[80] T. Dollevoet, F. Corman, A. D'Ariano, and D. Huisman, "An iterative optimization framework for delay management and train scheduling," *Flexible Serv. Manuf. J.*, vol. 26, no. 4, pp. 490–515, Dec. 2014.

[81] R. Larsen, M. Pranzo, A. D'Ariano, F. Corman, and D. Pacciarelli, "Susceptibility of optimal train schedules to stochastic disturbances of process times," *Flexible Serv. Manuf. J.*, vol. 26, no. 4, pp. 466–489, Dec. 2014.

[82] F. Corman, A. D'Ariano, and I. A. Hansen, "Evaluating disturbance robustness of railway schedules," *J. Intell. Transp. Syst.*, vol. 18, no. 1, pp. 106–120, Jan. 2013.

[83] G. Zaninotto, A. D'Ariano, D. Pacciarelli, and M. Pranzo, "Intelligent decision support for scheduling and rerouting trains on an Italian railway line," in *Proc. 16th IEEE ITSC*, 2013, pp. 779–784.

[84] F. Corman, A. D'Ariano, D. Pacciarelli, and M. Pranzo, "Dispatching and coordination in multi-area railway traffic management," *Comput. Oper. Res.*, vol. 44, pp. 146–160, Apr. 2014.

[85] S. Wegele and E. Schnieder, "Automated dispatching of train operations using genetic algorithms," in *Proc. Int. Conf. Comput. Railways*, 2004, pp. 775–784.

[86] X. Li and F. Lara-Rosano, "Adaptive fuzzy Petri nets for dynamic knowledge representation and inference," *Expert Syst. Appl.*, vol. 19, no. 3, pp. 235–241, Oct. 2000.

[87] A. Fay, "A fuzzy knowledge-based system for railway traffic control," *Eng. Appl. Artif. Intell.*, vol. 13, no. 6, pp. 719–729, Dec. 2000.

[88] Y. H. Cheng and L. A. Yang, "A fuzzy Petri nets approach for railway traffic control in case of abnormality: Evidence from Taiwan railway system," *Expert Syst. Appl.*, vol. 36, no. 4, pp. 8040–8048, May 2009.

[89] S. Milinković, M. Marković, S. Vesković, M. Ivić, and N. Pavlović, "A fuzzy Petri net model to estimate train delays," *Simul. Model. Pract. Theory*, vol. 33, pp. 144–157, Apr. 2013.

[90] H. Schaefer and S. Pferdmenges, "An expert system for real-time train dispatching," *Trans. Built Environ.*, vol. 7, pp. 27–34, 1994.

[91] Y. Larroche, R. Moulin, and D. Gauyacq, "SEPIA: A real-time expert system that automates train route management," *Control Eng. Pract.*, vol. 4, no. 1, pp. 27–34, Jan. 1996.

[92] C. S. Chang and B. S. Thia, "Online rescheduling of mass rapid transit systems: Fuzzy expert system approach," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 143, no. 4, pp. 307–316, Jul. 1996.

[93] T. K. Ho, J. F. Norton, and C. J. Goodman, "Optimal traffic control at railway junctions," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 144, no. 2, pp. 140–148, Mar. 1997.

[94] M. J. Dorfman and J. Medanic, "Scheduling trains on a railway network using a discrete event model of railway traffic," *Transp. Res. B, Methodol.*, vol. 38, no. 1, pp. 81–98, Jan. 2004.

[95] F. Li, Z. Gao, K. Li, and L. Yang, "Efficient scheduling of railway traffic based on global information of train," *Transp. Res. B, Methodol.*, vol. 42, no. 10, pp. 1008–1030, Dec. 2008.

[96] J. L. Espinosa-Aranda and R. García-Ródenas, "A discrete event-based simulation model for real-time traffic management in railways," *J. Intell. Transp. Syst.*, vol. 16, no. 2, pp. 94–107, Apr. 2012.

[97] M. Almodóvar and R. García-Ródenas, "On-line reschedule optimization for passenger railways in case of emergencies," *Comput. Oper. Res.*, vol. 40, no. 3, pp. 725–736, Mar. 2013.

[98] R. M. P. Goverde, "A delay propagation algorithm for large-scale railway traffic networks," *Transp. Res. C, Emerging Technol.*, vol. 18, no. 3, pp. 269–287, Jun. 2010.

[99] B. De Schutter and T. van den Boom, "Model predictive control for railway networks," in *Proc. IEEE/ASME Int. Conf. AIM*, 2001, pp. 105–110.

[100] B. De Schutter, T. van den Boom, and A. Hegyi, "A model predictive control approach for recovery from delays in railway systems," *Transp. Res. Rec.*, vol. 1793, pp. 15–20, 2002.

[101] T. van den Boom and B. De Schutter, "Modelling and control of discrete event systems using switching max-plus-linear systems," *Control Eng. Pract.*, vol. 14, no. 10, pp. 1199–1211, Oct. 2006.

[102] T. K. Ho and T. H. Yeung, "Railway junction traffic control by heuristic methods," *Proc. Inst. Elect. Eng.—Elect. Power Appl.*, vol. 148, no. 1, pp. 77–84, Jan. 2001.

[103] Q. Lu, M. Dessouky, and R. C. Leachman, "Modeling train movements through complex rail networks," *ACM Trans. Modeling Comput. Simul.*, vol. 14, no. 1, pp. 48–75, Jan. 2004.

[104] P. Weston *et al.*, "Minimising train delays in a mixed traffic railway network with consideration of passenger delay," in *Proc. 7th World Congr. Railway Res.*, Montreal QC, Canada, 2006.

[105] A. D. Middelkoop and L. Loeve, "Simulation of traffic management with FRISO," in *Proc. 10th Int. Conf. Comput. Railways X*, 2006, pp. 1–10.

[106] Y. Cui, "Simulation-based hybrid model for a partially automatic dispatching of railway operation," Ph.D. dissertation, Ins. Eisenbahn Verkehrswesen, Univ. Stuttgart, Stuttgart, Germany, 2010.

[107] N. Tomii, Y. Tashiro, N. Tanabe, C. Hirai, and K. Muraki, "Train rescheduling algorithm which minimizes passengers dissatisfaction," *Innovations in Applied Artificial Intelligence*, vol. 3533, ser. Lecture Notes in Computer Science. Berlin, Germany: Springer-Verlag, 2005, pp. 829–838.

[108] S. Kanai, K. Shiina, S. Harada, and N. Tomii, "An optimal delay management algorithm from passengers' viewpoints considering the whole railway network," *J. Rail Transp. Planning Manage.*, vol. 1, no. 1, pp. 25–37, Nov. 2011.

[109] K. Kumazawa, K. Hara, and T. Koseki, "A novel train rescheduling algorithm for correcting disrupted train operations in a dense urban environment," in *Proc. 11th Int. Conf. Comput. Syst. Des. Oper. COMPRAIL Other Transit Syst.*, 2008, pp. 565–574.

[110] M. Missikoff, "An object-oriented approach to an information and decision support system for railway traffic control," in *Proc. 1st Int. Conf. Knowl.-Based Intell. Electron. Syst.*, 1997, vol. 2, pp. 633–641.

[111] J. Barta, A. E. Rizzoli, M. Salani, and L. M. Gambardella, "Statistical modelling of delays in a rail freight transportation network," in *Proc. Winter Simul. Conf.*, 2012, pp. 1–12.

[112] N. J. Rezanova and D. M. Ryan, "The train driver recovery problem—A set partitioning based model and solution method," *Comput. Oper. Res.*, vol. 37, no. 5, pp. 845–856, May 2010.

[113] S. A. Afeez, "Train Dispatching: Heuristic Optimization," M.S. thesis, Comput. Eng., Dalarna Univ., Falun, Sweden, 2006.

[114] B. Fan, "Railway traffic rescheduling approaches to minimise delays in disturbed conditions," Ph.D. dissertation, School Electron., Elect. Comput. Eng., University of Birmingham, Birmingham, U.K., 2012.

[115] A. R. Albrecht, D. M. Panton, and D. H. Lee, "Rescheduling rail networks with maintenance disruptions using problem space search," *Comput. Oper. Res.*, vol. 40, no. 3, pp. 703–712, Mar. 2013.

[116] A. Mascis and D. Pacciarelli, "Machine scheduling via alternative graphs," Univ. Rome, Rome, Italy, Tech. Rep. DIA-46-2000, 2000.

[117] A. Mascis and D. Pacciarelli, "Job-shop scheduling with blocking and no-wait constraints," *Eur. J. Oper. Res.*, vol. 143, no. 3, pp. 498–517, Dec. 2002.

[118] A. Mascis, D. Pacciarelli, and M. Pranzo, "Scheduling models for short-term railway traffic optimisation," in *Computer-aided Systems in Public Transport*, vol. 600, Lecture Notes in Economics and Mathematical Systems. Berlin, Germany: Springer-Verlag, 2008, pp. 71–90.

[119] E. Quaglietta, F. Corman, and R. M. P. Goverde, "Stability analysis of railway dispatching solutions under a stochastic and dynamic environment," *J. Rail Transp. Planning Manage.*, pp. 137–149, 2013.

[120] M. Lüthi, G. Medeossi, and A. Nash, "Evaluation of an integrated real-time rescheduling and train control system for heavily used areas," in *Proc. IAROR Int. Semin. Railway Oper. Model. Anal.*, 2007, pp. 1–14.

[121] F. Peng, K. Tang, G. Chen, and X. Yao, "Population-based algorithm portfolios for numerical optimization," *IEEE Trans. Evol. Comput.*, vol. 14, no. 5, pp. 782–800, Oct. 2010.

[122] K. Tang, F. Peng, G. Chen, and X. Yao, "Population-based algorithm portfolios with automated constituent algorithms selection," *Inf. Sci.*, vol. 279, pp. 94–104, Sep. 2014.

[123] I. Sahin, "Railway traffic control and train scheduling based on inter-train conflict management," *Transp. Res. B, Methodol.*, vol. 33, no. 7, pp. 511–534, Sep. 1999.

[124] M. N. Omidvar, X. Li, Y. Mei, and X. Yao, "Cooperative co-evolution with differential grouping for large scale optimization," *IEEE Trans. Evol. Comput.*, vol. 18, no. 3, pp. 378–393, Jun. 2014.

[125] C. Ran and J. Yaochu, "A competitive swarm optimizer for large scale optimization," *IEEE Trans. Cybern.*, vol. 45, no. 2, pp. 191–204, Feb. 2015.

[126] K. Deb and H. Jain, "An evolutionary many-objective optimization algorithm using reference-point based non-dominated sorting approach—Part I: Solving problems with box constraints," *IEEE Trans. Evol. Comput.*, vol. 18, no. 4, pp. 577–601, Aug. 2013.

[127] H. Wang, L. Jiao, and X. Yao, "Two_Arch2: An improved two-archive algorithm for many-objective optimization," *IEEE Trans. Evol. Comput.*, vol. 19, no. 4, pp. 524–541, Aug. 2015.

[128] Q. Zhang and H. Li, "MOEA/D: A multiobjective evolutionary algorithm based on decomposition," *IEEE Trans. Evol. Comput.*, vol. 11, no. 6, pp. 712–731, Dec. 2007.

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