

Computer-based decision support for railway traffic scheduling and dispatching: A review of models and algorithms

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Abstract. This paper provides an overview of the research in railway scheduling and dispatching. A distinction is made between tactical scheduling, operational scheduling and re-scheduling. Tactical scheduling refers to master scheduling, whereas operational scheduling concerns scheduling at a later stage. Re-scheduling focuses on the re-planning of an existing timetable when deviations from it have occurred. 48 approaches published between 1973 and 2005 have been reviewed according to a framework that classifies them with respect to problem type, solution mechanism, and type of evaluation. 26 of the approaches support the representation of a railway network rather than a railway line, but the majority has been experimentally evaluated for traffic on a line. 94 % of the approaches have been subject to some kind of experimental evaluation, while approximately 4 % have been implemented. The solutions proposed vary from myopic, priority-based algorithms, to traditional operations research techniques and the application of agent technology.

1 Introduction

In most countries, the railway traffic system is a significant part of the backbone transport system as it is a major service provider for passenger traffic and freight transportation. Traffic and transport policies are striving towards decreasing road traffic pollution by e.g. increasing railway usage when appropriate. At the same time, the available railway systems are partly oversaturated creating bottlenecks on major links. An important issue is thus how to best use the existing capacity while ensuring sustainability and attractiveness.

Railway traffic scheduling is often considered a difficult problem primarily due to its complexity regarding size and the significant interdependencies between the trains. A railway network is generally far from as fine-grained as a road traffic network. The options to overtake and meet are very limited and depend on e.g. available side-tracks, switches, signalling facilities and the characteristics of the trains. Furthermore, in many countries the traffic is heterogeneous with trains carrying different types of cargo (commuters, long-distance passengers with connections, express freight, bulk

goods, etc) with different preferences, destinations and speed functions. All these specific attributes make the trains highly interdependent and their interplay complex to plan, overview and execute. In addition, the organisation of the railway traffic management differs between countries. In some, the operator and traffic manager are one and the same company while in some European countries the railway market is partly or fully deregulated with a separate authority governing the infrastructure and traffic management while several privatised and competing operators are using the tracks. The challenge is thus to comply with relevant preferences based on the available capacity to achieve and execute a robust and attractive timetable. This review surveys the research carried out within the area of railway scheduling and dispatching. Even though this is a rather well-known and studied problem domain, the number of reviews dealing with this topic is limited. In 1980, Assad [1] presented a survey of different models for rail transportation including optimisation, queuing, simulation approaches, etc. Later, a survey by Cordeau et. al. [17] was published and with a specific focus on various optimisation models for the most commonly studied railway problems.

The aim of this paper is to classify and compare the various approaches for railway traffic scheduling in more detail than previous surveys which instead have had a wider scope. Furthermore, new methodologies such as agent technology have appeared during the last years and these need to be taken into account and be compared to more traditional approaches. The next chapter will present the scope of this paper, followed by a description of the problem domain. The classification and review framework that has been applied is then presented. A discussion of the results from the review and some observations are later provided, followed by conclusions and directions for future research.

2 Scope

The focus here is railway traffic scheduling with an emphasis on slot allocation (i.e. the assignment of entry and exit times for trains on track sections) but also to some extent route allocation (i.e. which track sections to use to get from origin to final destination). That is, if we have a set of trains with individual and possibly competing requests for track capacity, how should the trains be scheduled to reach the scheduling objective(s)? Thus, primarily the perspective of an infrastructure provider that may schedule trains of several train traffic operators (rather than an operator scheduling its services exclusively on its own tracks) is in focus. Hence, rail transport scheduling, i.e. primarily scheduling of the available resources such as fleets of vehicles and staff for specific railway services, is not explicitly considered even if there are some common aspects. For these types of problems we refer to [1], [18], [6], [19], and [17]. Furthermore, approaches which focus on periodic timetabling, timetable synchronisation and sensitivity and robustness analysis of timetables are not reviewed explicitly either and we refer instead to e.g. [50], [58] and [48]. Even though the task of analysing and predicting the effects of a disturbance is a part of solving disturbances, research specifically focusing on that is not included, but can instead be found in e.g. [28].

A distinction is here made between tactical scheduling, operational scheduling and re-scheduling of railway traffic. Scheduling (or timetabling) is the process of constructing a schedule from scratch, while re-scheduling (or dispatching) indicates that a schedule already exists and will be modified. The scheduling can also be carried out with different time perspectives, i.e. on a tactical or operational (real-time) level. In Europe, there is a tradition of creating master schedules that specify a strict route and timetable for each train on a tactical level with the intention to execute it in real-time. The scheduling may thus involve both route choice and slot allocation, where a slot is the time window a certain train is planned to use a specific track section. For obvious reasons, scheduling of passenger traffic is often carried out on a tactical basis.

Operational scheduling is commonly used for example in North America (and for freight transport scheduling). Instead of creating a master schedule a long time before it is actually put into action, the operational scheduling takes place not long before departure. The routes are then generally already fixed but not the slots. Re-scheduling is related to disturbance handling, i.e. assigning new slots to the trains to minimise their deviations from the established timetable.

This review does not include an explicit survey of the tools used by the railway authorities or other stakeholders. Included are 48 approaches that have been published during the time period 1973-2005. Some approaches have been described in several publications, but only the references to the most recent and detailed descriptions are included here.

3 Domain description

Tactical scheduling, operational scheduling and re-scheduling have the basic problem and limitations in common. The kernel of the problem is the conflicts that arise when two or more trains want to occupy the same part of the network simultaneously. The railway network is usually divided into blocks (i.e. separate track sections) where each block can normally hold only one train at a time in order to maintain the required safety level (referred to as *line blocking*). Conflicts could appear when a train is too close behind another train travelling in the same direction, or when two trains are travelling in opposite directions and would meet within the same block. Due to the line blocking, trains are not allowed to get too close and not to meet within a block. The conflicts need to be solved not only taking into consideration one isolated conflict, but also the effect it will have on the surrounding traffic later on in time. Conflicts may thus be interdependent and nested. Solving one may consequently create additional conflicts or resolve others. The number of possible solutions can become very large depending on e.g. the network structure, the amount of traffic and type of trains.

Fig. 1 provides an illustration of a bi-directional (two-way traffic) single-tracked railway line with line blocking, and where a conflict has emerged due to a deviating train (i.e. Train 1). When Train 1 departs from Station E, it malfunctions temporarily and becomes significantly delayed. Since the schedule of Train 1 interferes with foremost Train 2, Train 2 becomes delayed as well due to the restriction of not

allowing two trains to use a block (i.e. between Station E and F) simultaneously. The circle indicates the violation of the restriction that would take place if the initial schedule of the trains was to be followed. Instead, Train 2 must wait for Train 1 which causes additional conflicts and possibly delays Train 3 and 4 as well depending on how the situation is resolved.

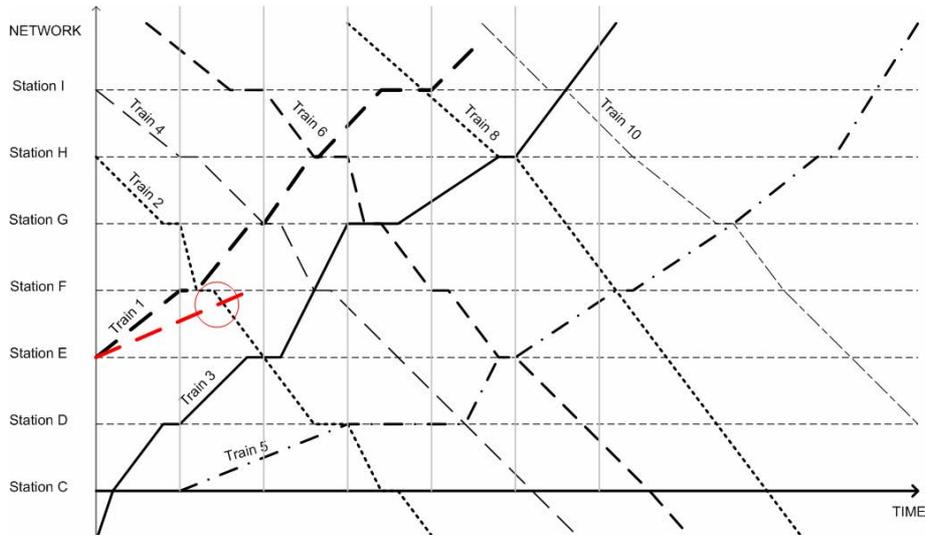


Fig. 1. A time-distance graph describing the railway traffic network between Station I and Station C and the scheduled traffic.

Even though the three types of scheduling problems have the main kernel in common, there are some significant differences regarding context, time frame and objective(s). Tactical scheduling usually involves scheduling for a large traffic network for a long time horizon (sometimes up to a year, but on a day-to-day basis) and the time available for creating the timetable may be several months. Operational scheduling has a shorter time frame and is initiated closer in time to the departure of the trains. The objective of tactical scheduling may be more complex reflecting the demand of several stakeholders and taking into account infrastructure maintenance. Operational scheduling balances also competing requests, but time is more of an issue and some new constraints such as definite time windows and connections may have been introduced.

Re-scheduling is initiated when a deviation from an initial schedule occurs with the aim to minimise the overall delays. The re-scheduling may need to be carried out within a short time frame (minutes or seconds) and not be able to or have time to explicitly consider the interests of all stakeholders. However, connections and the consequential importance of pairing slots, platforms and tracks are introduced; see e.g. [76], [44] and [12]. Those considerations are partly also taken into account when creating the

initial timetable but the liberties are fewer during timetable execution and re-scheduling since some parameters cannot be changed (i.e. rolling stock is already allocated, timetables for passengers are published and platforms announced, track maintenance is planned or have already started, etc).

In practice, tactical and operational scheduling are often carried out using a combination of computational tools and human expertise while for re-scheduling, human expertise and rules of thumb often is the dominating procedure.

4 Classification framework

The framework applied classifies the approaches according to the scheme in [Table 1](#).

Table 1. Classification and review framework.

PROBLEM TYPE PLANNING PERSPECTIVE: Tactical scheduling Operational scheduling Re-scheduling INFRASTRUCTURE REPRESENTATION: Line (L), Network (N) Single- (S), Double- (D), (N)-tracked, Uni- (U), or Bi-(B)directional OBJECTIVE(S) SPECIAL CONSIDERATION(S)	CONTROL Centralised (C) Hierarchically distributed (H) Distributed (D) Localised (L)
	PROBLEM FORMULATION
	SOLUTION MECHANISM
	EVALUATION LEVEL 1. Conceptual approach 2. Simulated experiments with artificial data 3. Simulated experiments with real data 4. Field experiments 5. Implemented (deployed)
	PROBLEM INSTANCE AND SIZE

Problem type specifies which problem the reviewed approach is assigned to handle regarding the *planning perspective*, *infrastructure representation*, *objective(s)*, and *special considerations* in mind. As previously described, tactical scheduling is the most long-term planning perspective, whereas operational scheduling concerns scheduling close in time to departure. Re-scheduling focuses on the real-time re-planning of an existing timetable when deviations from it have occurred. *Infrastructure representation* describes what kind of railway infrastructure that the approach can be applied to. A *line* is a sequence of segments between two major stations with possibly several intermediate stations, while a *network* is composed of one or several junctions of lines. The classification of whether an approach can represent a line or also a network is based upon its problem formulation. E.g. if the problem formulation assumes that the segments and/or stations are sequenced into a line and that the traffic traverses them in that certain order, a network can not be represented by that approach.

Each segment is composed of one or several parallel track sections (i.e. blocks). The maximum number of tracks within a segment that an approach can represent is referred to as *single*, *double* or *N*. If an approach can handle tracks permitting traffic

in one direction, it is denoted ‘U’ (uni-directional), while if also (or instead) two-way traffic is accounted for it is denoted ‘B’ (bi-directional). Fig. 2 provides an illustration of the terminology used. Double-tracked segments are often in practice uni-directional, where one side of the segment is allocated to traffic in one direction and the other allows traffic in the other direction. The reason behind this restriction is that it facilitates the traffic management, or the signalling infrastructure is limited to show signals in only one direction per track section. However, in dense traffic areas, the tracks may need to be used for traffic in either direction (if the signalling infrastructure permits) since there may be an imbalance in the traffic volume during some parts of the day or some express trains may need to overtake slower trains. Allowing trains to run in both directions obviously increases capacity and flexibility but also increases the complexity.

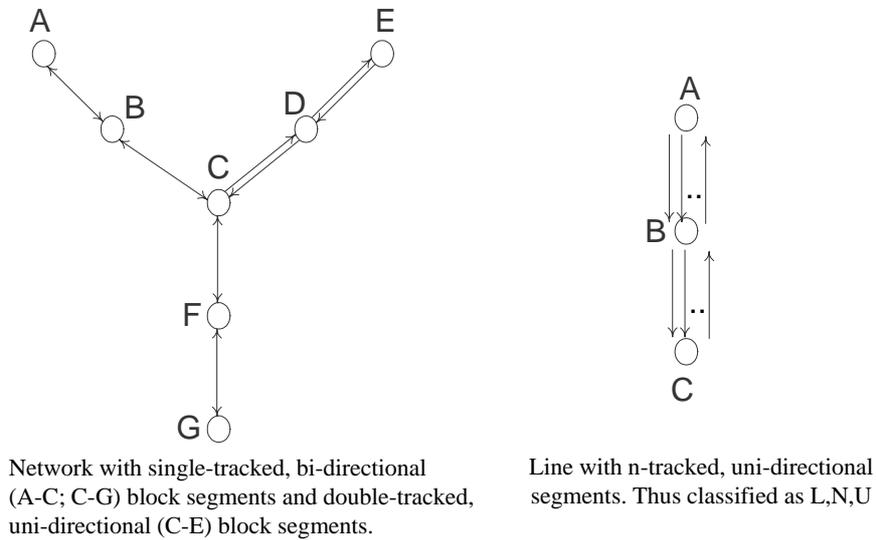


Fig. 2. Illustration of terminology used for types of infrastructure representation.

Objective(s) state the purpose and goal of the solution mechanism (e.g. minimising travel time, operating costs or maximising utility). *Special considerations* (e.g. connecting trains, platform assignment, and train preferences) specify if the approach account for other characteristics and constraints beside line blocking and logical relations.

Besides classifying the problem type, we consider the *problem formulation*, the *control strategy* and *solution mechanism* applied. The formulation refers to the representation of the solution space. Most common are mathematical models such as MIP (Mixed Integer Programme), CSP (Constraint Satisfaction Problem), CP (Constraint Programme) and other models based on e.g. graph theory and network modelling. The control strategy represents how to search through the solution space

defined by the problem formulation. Four main control strategies for solving the problem can be found; centralised (C), hierarchically distributed (H), distributed (D) and localised (L). A centralised approach refers to when the problem is solved as one instance. That is, the full problem is considered simultaneously such as during some form of enumeration as in classical Branch and Bound, see e.g. [57]. A distributed (or decentralised) approach divides the main problem into sub-problems with the aim of solving them partly in parallel. The relation between the sub-problems (i.e. how they together form the main problem) needs then to be formulated and the solution processes need to be synchronised. If there is a hierarchy and some kind of central and synchronising control of the sub-problem solving, this is referred to as hierarchically distributed (e.g. classic Lagrangian relaxations, see [23]). If the sub-problems instead are solved independently, this is referred to as a distributed strategy. Sub-problems are usually solved in either a cooperative or competitive environment. In the cooperative environment, the sub-problems have a common goal and adjust to the overall best actions. In a competitive environment, all or some of the sub-problems are solved with individual and sometimes competing interests. A commonly used competitive environment is auctions, which often is referred to as a market-based mechanism. For more information see e.g. [74]. The localised strategy is very similar to the distributed; the problem is divided and its parts allocated to e.g. the stations, but the stations do not synchronise their behaviour in any way.

Examples on solution mechanisms are different types of heuristics such as Local Search (LS), Tabu Search (TS, see [27]) or Simulated Annealing (SA, see [39]). Branch and Bound (B&B), Lagrangian relaxations, expert systems and more straightforward tailored methods such as full or partial enumeration or priority-based conflict resolution are other examples. For further information on related terminology, we refer to [62] and [57].

The evaluation level of an approach refers to how developed and evaluated it is with regard to what is stated in the publication(s). That is, if it is a conceptual description, has been experimentally applied to a problem instance of a real or fictional setting, been evaluated in a real setting (field experiments), or has been implemented. By implemented, we mean that the approach has been, or is, a deployed system. The problem instance and size specifies the maximum size (number of stations, segments and trains) of the problem instance that the approach has been applied to (while the size of the practical problem in mind may be larger but not considered experimentally).

Finally, we have also tried to compare the advantages and disadvantages of the suggested modelling and solution approaches, considering the varying set of prerequisites during the publication year and the context. Generally, it would be interesting to have a quantitative benchmark that compares e.g. the speed and optimality measure of the approaches reviewed. However, due to lack of information on those attributes and the overall dominating use of individual data instances, such an analysis has not been possible.

5 Discussion of review results

The publications reviewed were published during the time period 1973-2005 and a summary of the approaches is presented in the [Appendix](#). The terminology used differs between the publications reviewed. When discussing the problem size by means of number of stations, segments and trains in the tables in the [Appendix](#), we have taken the liberty to translate the given settings into number of stations and segments, when possible. [Table 2](#) and [Table 3](#) present the number of approaches that considers the different types of infrastructure. ‘Unclassified’ means that the publication(s) did not provide enough information for a complete classification. Since the objectives and premises for tactical and operation scheduling and re-scheduling vary, different special side-constraints are applied. As can be seen in [Table 4](#), more details of the infrastructure are considered during scheduling while preferences related to trains and operators are more commonly considered during re-scheduling. The vast majority of the approaches adopts a quite simplified representation of stations and do not consider the potential crossing of train paths and allocation of tracks within stations.

Table 2. Frequency of infrastructure representation per problem type, where U = uni-directional, B = bi-directional, S=single-tracked, D=double-tracked, and N=n-tracked refer to the segment structure (the non-station segments).

Infrastructure	Tactical scheduling	Operational scheduling	Re-scheduling	Total
US Line	2	0	2	4
US Network	1	0	0	1
UD Line	1	0	2	3
UN Network	0	0	1	1
BS Line	4	4	3	11
BS Network	1	2	1	4
BS,UD Line	3	0	0	3
BN Line	1	0	0	1
BN Network	7	1	8	16
(Unclassified) Network	0	0	4	4
Total	20	7	21	48

Table 3. Frequency of infrastructure representation per problem type referring to the segment structure (the non-station segments).

Infrastructure	Tactical scheduling	Operational scheduling	Re-scheduling	Total
Line	11	4	7	22
Network	9	3	14	26
Uni-directional	4	0	5	9
Bi-directional	16	7	12	35
Undefined	0	0	4	4
Single-tracked	8	6	6	20
Double-tracked	4	0	2	6
N-tracked	8	1	9	18
Unclassified	0	0	4	4

Table 4. Special side-constraints and the number of approaches that considers them.

Special consideration	Tactical scheduling	Operational scheduling	Re-scheduling	Total
Switches, track connections	1	-	1	2
Station and platform characteristics	4	-	-	4
Time windows	1	-	1	2
Rolling stock/ Crew schedules	-	1	1	2
Train connections	-	-	3	3
Platform allocation	-	-	3	3

Regarding the problem formulations adopted, the infrastructure and traffic are modelled in a few main ways. It is common to formulate an explicit MIP using binary variables to represent the sequence of trains on the segments, and continuous variables for the entry and exit times of each train on each segment or specific track. The line or network is then explicitly composed of segments, while the nodes between the segments (intersections, meet points, stations, etc.) are implicitly modelled. A second formulation models instead the stations explicitly and the segments between

implicitly. The binary variables and their values specify then in which order the trains enter and exit the stations (i.e. their tracks) and according to that continuous variables specify when a train arrives at and leaves the corresponding stations and tracks.

It is difficult to assess what the advantages and disadvantages of each alternative are. The second formulation (i.e. modelling stations and meet-points explicitly) seems to be less flexible to extend and use for a network since a station may be connecting several segments (e.g. main stations that serve as junctions for several lines) while a segment only has two end points. The first formulation seems to handle such an increased complexity better than the second formulation, but the advantage of the second formulation is that constraints related to station attributes (e.g. usage of platforms and switches) are easier to handle. A combination of the two formulations is to model both stations and non-station segments explicitly. That facilitates the specification of detailed restrictions for all elements, but the number of variables will consequently increase.

Another common formulation is to have a graph model of arcs and nodes representing the binary variables that specify the order of trains on the segments in the MIP. A sequence of arcs then needs to be created while considering a set of constraints. Using an object-oriented or a discrete-event formulation of the problem is another common representation.

The formulations previously described use variables to represent the start and end times of the slots. The majority uses continuous variables for the times, while a few discretize the time into time units of one or several minutes. Each time unit per train and block is then represented by a binary variable where the value '1' specifies that the time unit for that block is used by the specific train. This way, the sequence of trains on the blocks does not have to be explicitly modelled but is implicitly considered already. On the other hand, discretizing time may result in a significant amount of binary variables if small time units are used. For re-scheduling and scheduling dense traffic, it may be necessary to use small time units in order to utilise the infrastructure to the full extent. Five approaches have used discrete time units where four of them address tactical scheduling, i.e. [5], [51], [8] and [35], and one re-scheduling, i.e. [64].

The slots can also be discretized into a set of fixed slots (block- and time-dependent) where the objective then is to create the optimal and feasible combination of slots for each and all trains. This formulation can be seen foremost in combination with the use of MAS and auctions. Auctioning is becoming more commonly used within scheduling and the use of agent technology is more commonly adopted in the traffic and transport domain [21]. There are several other mechanisms of allocating track capacity and a detailed discussion about the different principles can be found in [26]. One of the problems that hamper the use of auctions and its applicability in the railway domain is the need to have a discrete set of subjects to bid for. Railway slots are to some extent an infinite and continuous set of options and are thereby difficult to effectively translate into a discrete set. The main challenges for these approaches are the formulation of the bid generation (including handling multiple interdependencies) and the set-up for negotiation and communication within the auctions. Since several of the publications do not outline these parts of their approach (only the general bidding procedure and objective) and apply the proposals on relatively small data sets, it is difficult to assess the general applicability.

Difficulties in handling large problems and scalability issues are sometimes used as arguments to apply distributed (including hierarchically distributed) methods such as auctions instead of centralised ones. Even though the vast majority of the publications reviewed use a centralised approach, there is a significant usage of distributed problem solving (see [Table 5](#)). Tactical scheduling has a comparably less time restriction and favours solution quality rather than algorithmic speed. Consequently centralised solution methods are dominating while five of the 20 approaches reviewed apply a distributed solution mechanism. Three of them ([\[4\]](#), [\[2\]](#), [\[3\]](#) and [\[35\]](#)) use agent technology and MAS to solve the problem and two approaches ([\[4\]](#) and [\[35\]](#)) apply a market-based strategy. Three approaches apply Lagrangian relaxations.

Only two approaches for re-scheduling consider a distributed mechanism and four adopt a localised strategy. The main difference between having a distributed (and hierarchically distributed) and a localised strategy is that the synchronisation of the distributed approach may require significant computational effort for the overhead communication and is (like the centralised approach) sensitive to an increase in problem size and set-up of the problem structure while the more localised strategy is (time-wise) not as dependent on the problem size. However, the localised strategy may result in a sub-optimisation and less robust and reliable solutions. There is thus an obvious trade-off that needs to be made.

Table 5. Frequency of control strategy used per scheduling problem. *One approach for tactical scheduling evaluates both a hierarchically distributed control strategy and a centralised one.

Planning perspective	Centralised	Hierarchically distributed*	Distributed	Localised
Tactical scheduling	16	3	2	0
Operational scheduling	7	0	0	0
Re-scheduling	15	0	2	4
Total	38	3	4	4

The use of context-dependent and tailored solution methods are more common for operational scheduling and re-scheduling purposes than for tactical scheduling. Several approaches apply myopic mechanisms that do not consider the secondary effects of a decision and thus this may make them less appropriate for the general scheduling problem. Some approaches propose enumeration techniques, which for small problem instances may be sufficient and successful but for a larger problem, interdependent conflicts and secondary effects will arise. It is also quite common, especially for the re-scheduling problem, to use expert systems and priority rules. Those approaches incorporate the current work process of the dispatchers in many ways by translating tacit knowledge and rules of thumb into computerised systematic reasoning. This differs from the all-human decision-making process as it has a larger capability to consider a longer time horizon with more complex and nested decisions.

In [Table 6](#), the number of approaches per evaluation level and scheduling problem is presented and [Table 7](#) presents the frequency of infrastructure type used in the

evaluations. As can be seen, many of the approaches reach the stage of being experimentally evaluated but several for rather modest problem instances. An increase in the railway traffic volume in several countries as well as the increase of computational capacity would make one expect a trend towards increasing size of the problem instances used in experiments. However, no significant relation between infrastructure type and problem size used for evaluation and publication year can be seen for tactical or operational scheduling. The focus on re-scheduling seems to have increased the past years and the size of the problem instances used to evaluate the approaches for tactical scheduling and re-scheduling are interesting enough similar in size and type.

Table 6. Overview of the number of approaches on the different evaluation levels.

Planning perspective	Conceptual approach	Simulated w. artificial data	Simulated w. real data	Field experiment	Implemented
Tactical scheduling	1	6	13	0	0
Operational scheduling	0	3	2	1	1
Re-scheduling	0	3	13	4	1
Total	1	12	28	5	2

In railway networks, the demand for slots is sometimes larger than the available capacity and the different trains have varying characteristics and use different parts of the network. Hence, the traffic interplay may be too complex to schedule operationally and needs to be scheduled on a tactical level. Despite the complexity of the tactical scheduling and that nine out of those 20 approaches are able to represent a network structure, only two of them have been evaluated for a network structure, see [Table 7](#).

Table 7. Overview of the number of approaches that has used a certain infrastructure representation in the evaluation.

Planning perspective	Line	Network	Not classified
Tactical scheduling	17	2	1
Operational scheduling	7	0	0
Re-scheduling	14	6	1
Total	38	8	2

The variety of solution methods applied is impressive, providing innovative ideas which often have been quantitatively evaluated (see a summary of the review in the [Appendix](#)). Unfortunately, the choice of method is rarely motivated. Some publications state that the problem in focus is NP-hard and too difficult to solve to

optimality and instead apply a heuristic approach. The reason is claimed to be the growing complexity of the problem due to an exponentially increasing number of solutions with the increase in problem size and binary variables. Theoretically, a problem with n binary variables could generate a search space of 2^n possible solutions. That may very well be true for a certain problem size and formulation. However, most publications make no attempt to show this for their problem or try solve the problem instance to optimality, but just assume it is too difficult. Due to the interdependencies (infeasibility and transitivity relations) between the binary variables, a large number of constraints are present and reduce the solution space significantly. Additional trains and segments may add increased complexity due to an increase in number of variables, but they may also decrease the search space since the number of restrictions may increase as well. Therefore, general conclusions on the proportional relation between the number of binary variables, size of solution space and computation time are difficult to make. In addition, the complexity of the problem is also dependent on the input data and the objective function. For tactical scheduling six approaches have conducted an optimality check and one compares its results to the Nash Equilibrium. Three approaches for operational scheduling have been subject to an optimality check and five of the re-scheduling approaches. The presence of optimality checks is not strictly related to publication year, i.e. approaches in the early 1990's as well as recently published approaches have been evaluated, while several of the recently published are non-evaluated. Several of the approaches that have been subject to an optimality check have used comparably large problem instances.

It is difficult to assess the applicability of the different formulations and solution mechanisms. Obviously, it depends on the practical problem characteristics. Earlier models of the railway scheduling problems are to a great extent still applicable, since the structure of the railroad has not changed much. However, whether simplifications and assumptions made earlier are valid today with respect to changes in traffic flows and density is not clear. Moreover, the solution methods have been developed significantly since the access to computational capacity has increased dramatically along with the opportunity to solve larger problems than possible before. The trend of favouring standardised techniques gives an indication of this.

6 Conclusions and future research

The variety of proposals is large, and many researchers have evaluated their approach with simulation experiments using real data. However, few incorporate previous work but instead create own mechanisms. That is, many publications mention related work while few seem to really consider whether it is relevant for their context. Furthermore, the choice of problem formulation and solution mechanism is often neither motivated nor compared to alternative approaches. However, a quantitative benchmark requires the researchers to have access to and use the same problem instances as previous researchers of earlier work. There is thus a need to have and to use publicly available and acknowledged problem instances for the railway scheduling problems as in several problem areas within the operations research community. To our knowledge there are currently none available. Furthermore, several publications do not provide

computational results related to speed or size of problem instance and possible scalability issues. An extended description of the size and characteristics of the practical problem in mind would also facilitate the comparison to other approaches and its applicability for a different setting. As mentioned earlier, it is common to assume that optimality is hard to achieve, while few attempts to do so are described. A comparison of computational results with results from an attempted optimisation (i.e. a lower bound or a gap) would be of interest whether it has been successful or not.

As we could see in the review, new techniques are arising, such as the use of auctions and agent technology. However, the challenges regarding synchronising the (partial) parallel solving of a distributed problem and how to generate and handle the selection of slots need to be presented further as does the impact on computational efficiency.

To conclude; researchers are encouraged to use well-known, common problem instances so that the research community can benchmark approaches. That assumes, however, that such are available. Furthermore, experiments should be carried out with respect to different problem sizes (and related to the practical problem size) and the corresponding computational-efficiency of the mechanism should be presented. Several approaches seem promising, and further experimentation and development would be of great interest. In addition, any attempts to achieve optimum solutions are recommended and the results should be presented. Finally, an extended discussion of the practical viability of the suggested approaches, motivation of the simplifications made and description of the real problems in mind would support conclusions and research results even further.

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References

1. Assad, A.: Models for rail transportation. *Transportation Research Part A*, Vol. 14A. (1980) 205- 220
2. Blum, J., Eskandarian, A.: Domain-specific genetic agents for flow optimization of freight railroad traffic. *Proceedings of the 8th International Conference on Computers in Railways*, June 12-14, Wessex Institute of Technology, Lemnos, Greece (2002a)
3. Blum, J., Eskandarian, A.: Enhancing Intelligent Agent Collaboration for Flow Optimization of Railroad Traffic. *Transportation Research Part A*, Vol. 36. (2002b) 919-930
4. Brewer, P.J., Plott, C.R.: A binary conflict ascending price (BICAP) mechanism for the decentralized allocation of the right to use railroad tracks. *International Journal of Industrial Organization* 14. (1996) 857–886

5. Brännlund, U., Lindberg, P.O., Nöu, A., Nilsson, J-E.: Railway timetabling using Lagrangian relaxation. *Transportation Science*, Vol. 32, No. 4, (1998) 358-369
6. Bussieck, M.R., Winter, T., Zimmermann, U.T.: Discrete optimization in public rail transport. *Mathematical Programming*, Vol. 79, (1997) 415-444
7. Cai, X., Goh, C.J., Mees, A.I.: Greedy heuristics for rapid scheduling of trains on single tracks. *IIE Transactions* 30. (1998) 481-493
8. Caprara, A., Fischetti, M., Toth, P.: Modeling and solving the timetabling problem. *Operations Research*, Vol. 50, No. 5. (2002) 851-861
9. Carey, M.: Extending a train pathing model from one-way to two-way track. *Transportation Research Part B*, Vol. 28B, No. 5. (1994a) 395-400
10. Carey, M.: A model and strategy for train pathing with choice of lines, platforms and routes. *Transportation Research Part B*, Vol. 28B, No. 5. (1994b) 333-353
11. Carey, M., Lockwood, D.: A model, algorithms and strategy for train pathing. *Journal of the Operational Research Society* 46. (1995) 998-1005
12. Carey, M., Carville, S.: Scheduling and platforming trains at busy complex stations. *Transportation Research Part A*, Vol. 37. (2003) 195 –224
13. Chang, S-C., Chung, Y-C.: From timetabling to train regulation-a new train operation model. *Information and Software Technology*, Vol. 47. (2005) 575-585
14. Cheng, Y.: Hybrid simulation for resolving resource conflicts in train traffic rescheduling. *Computers in Industry*, Vol. 35. (1998) 233–246
15. Chiang, T-W., Hau, H-Y., Chiang, H-M., Ko, S-Y., Hsieh, C-H.: Knowledge-based system for railway scheduling. *Data and Engineering* 27. (1998) 289-312
16. Chiu, C.K., Chou, C.M., Lee, J.H.M., Leung, H.F., Leung, Y.W.: A Constraint-Based Interactive Train Rescheduling Tool. *Constraints* 7. (1996) 167-198
17. Cordeau, J-F., Toth, P., Vigo, D.: A survey of optimization models for train routing and scheduling. *Transportation Science*, Vol. 32, No. 4. (1998) 380-404
18. Crainic, T.G., Laporte, G.: Planning models for freight transportation. *European Journal of Operational Research* 97. (1997) 409-438
19. Crainic T.G.: A survey of optimization models for long-haul freight transportation, Publication CRT-98-67. Centre de recherche sur les transports. Université de Montréal., Canada (1998)
20. D'Ariano, A., Pranzo, M.: A real time train dispatching system based on blocking time theory. *Proceedings of the 8th TRAIL 8th Annual Congress 2004 - A world of transport, infrastructure and logistics*. Delft, DUP Science. ISBN 90-407-2555-1. (2004) 129-152
21. Davidsson, P., Henesey, L., Ramstedt, L., Törnquist, J., Wernstedt, F.: An analysis of agent-based approaches to transport logistics. *Transportation Research Part C: Emerging Technologies*, Vol. 13, Issue 4. (2005) 255-271
22. Dorfman, M.J., Medanic, J.: Scheduling trains on a railway network using discrete-event model of railway traffic. *Transportation Research Part B*, Vol. 38. (2004) 81-98
23. Fischer, M.L.: The Lagrangian relaxation method for solving integer programming problems. *Management Science* 27. (1981) 1-18
24. Fukumori, K.: Fundamental scheme for train scheduling: Application of range-constriction search. A.I. Memo No. 596. Massachusetts Institute of Technology Artificial Intelligence Laboratory, USA (1980)
25. Ghoseiri, K., Szidarovszky, F., Asgharpour, M.J.: A multi-objective train scheduling model and solution. *Transportation Research Part B*, Vol. 38. (2004) 927-952
26. Gibson, S.: Allocation of capacity in the rail industry. *Utilities Policy* 11. (2003) 39–42
27. Glover, F., Laguna, M.: *Tabu Search*, Kluwer Academic Publishers, Dordrecht, Netherlands (1997)
28. Hallowell, S., Harker, P.: Predicting on-time performance in scheduled railroad operations: Methodology and application to train scheduling. *Transportation Research Part A*, Vol. 32, No. 4. (1998) 279-296

29. Hellström, P.: Analysis and evaluation of systems and algorithms for computer-aided train dispatching. Licentiate thesis, Uppsala University, Sweden (1998)
30. Hellström, P., Sandblad, B., Frej, I., Gideon, A.: An evaluation of algorithms for Computer-Aided Train Dispatching. In: Hellström, P.: Analysis and evaluation of systems and algorithms for computer-aided train dispatching. Licentiate thesis, Uppsala University, Sweden (1998)
31. Higgins, A., Kozan, E.: Heuristic techniques for single line train scheduling. *Journal of Heuristics* 3. (1997) 43-62
32. Ho, T.K., Yeung, T.H.: Railway junction traffic control by heuristic methods. *IEEE Proceedings Electr. Power Appl.*, Vol. 148, No. 1. (2001) 77-84
33. Ingolitto, L., Barber, F., Tormos, P., Lova, A., Salido, M., Abril, M.: An Efficient Method to Schedule New Trains on a Heavily. In: (eds.) Reyes, C.A., Gonzales, J.A.): *Proceedings of Advances in Artificial Intelligence - IBERAMIA 2004, 9th Ibero-American Conference on AI*, Puebla, Mexico, November 22-26, 2004. *Lecture Notes in Computer Science*. Springer Verlag. (2004) 164-173
34. Isaai, M.T., Singh, M.G.: Hybrid applications of constraint satisfaction and meta-heuristics to railway timetabling: A comparative study. *IEEE Transactions on Systems, Man and Cybernetics – Part C: Applications and Reviews*, Vol. 31, No. 1. (2001) 87-95
35. Isacsson, G., Nilsson, J-E.: An experimental comparison of track allocation mechanisms in the railway industry. *Journal of Transport Economics and Policy*, Vol. 37, No. 3. (2003) 353-381
36. Iyer, R.V., Gosh, S.: DARYN – A distributed decision-making algorithm for railway networks: Modeling and Simulation. *IEEE Transactions on Vehicular Technology*, Vol. 44, No. 1. (1995) 180-191
37. Jia, L-M., Zhang, X-D.: Distributed intelligent railway traffic control based on fuzzy decisionmaking. *Fuzzy Sets and Systems*, Vol. 62, Issue 3. (1993) 255-265
38. Jovanovic, D.: Improving railroad in-time performance: models, algorithms and applications. Ph. D. thesis, Decision Science Department, Wharton School, University of Pennsylvania, USA (1989)
39. Kirkpatrick, S.: Optimization by Simulated Annealing - Quantitative Studies. *Journal of Statistical Physics* 34. (1984) 975-986
40. Kitahara, F., Kera, K., Bekki, K.: Autonomous decentralized traffic management system. *Proceedings of International workshop of Autonomous Decentralized Systems 2000*. (2000) 87-91
41. Koch, W.: A low cost tool for rescheduling in regional public transport systems. *Proceedings of the 9th IFAC Symposium on Control in Transport Systems 2000*. June 13-15. Braunschweig, Germany (2000)
42. Komaya, K., Fukuda, T.: A knowledge-based approach for railway scheduling. *Proceedings for the Seventh IEEE Conference on Artificial Intelligence for Applications*. IEEE Comput. Soc. Press. (1991) 404-411
43. Kraay, D., Harker, P.: Real-time scheduling of freight railroads. *Transportation Research Part B*, Vol. 29B, No. 3. (1995) 213-229
44. Kroon, L.G., Romeijn, H.E., Zwaneveld, P.J.: Routing trains through railway stations: complexity issues. *European Journal of Operational Research* 98. (1997) 485-498
45. Lamma, E., Mello, P., Milano, M.: A distributed constraint-based scheduler. *Artificial Intelligence in Engineering* 11. (1997) 91-105
46. Larroche, Y., Moulin, R., Gauyacq, D.: SEPIA: a real-time expert system that automates train route management. *Control Engineering Practice*, Vol. 4, Issue 1. (1996) 27-34
47. Lee, T.S, Gosh, S.: Stability of RYNSORD – A decentralized algorithm for railway networks under perturbations. *IEEE Transactions on Vehicular Technology*, Vol. 50, No.1. (2001) 287-301

- 48.Liebchen, C., Moehring, R.: The Modeling Power of the Periodic Event Scheduling Problem: Railway Timetables - and Beyond. Proceedings of the 9th International Conference on Computer-Aided Scheduling of Public Transport (CASPT). San Diego, USA (2004)
- 49.Lin, H-C., Hsu, C-C.: An interactive train Scheduling workbench based on Artificial Intelligence. Proceedings from International Conference on Tools with Artificial Intelligence (ICTAI) 1994. (1994) 42-48
- 50.Lindner, T.: Train Schedule Optimization in Public Rail Transport. Ph.D. thesis. Technische Universität Braunschweig, Germany (2000)
- 51.Mackenzie S.: Train timetabling on complex networks. Proceedings from the Conference on Railway Engineering 2000 (CORE2000), Adelaide, Australia (2000)
- 52.Missikoff, M.: An object-oriented approach to an information and decision support system for railway traffic. Proceedings for the 1997 First International Conference on Knowledge-Based Intelligent Electronic Systems - KES '97, Vol. 2. (1997) 633-641
- 53.Nilsson, J-E.: Allocation of track capacity: Experimental evidence on the use of priority auctioning in the railway industry. International Journal of Industrial Organization 17. (1999) 1139–1162
- 54.Oliveira, E., Smith, B. M.: A hybrid constraint-based method for single-track railway scheduling problem. Report 2001:4, Research report series. School of Computing, University of Leeds, UK (2001)
- 55.Pacciarelli, D., Pranzo, M.: A Tabu Search algorithm for the railway scheduling problem. Proceedings of MIC '2001- 4th Metaheuristics International Conference, Porto, Portugal. (2001) 159-163
- 56.Pacciarelli, D., Mascis, A., Pranzo, M.: Scheduling Models for Short-Term Railway Traffic Optimization. Proceedings of the 9th International Conference on Computer-Aided Scheduling of Public Transport (CASPT). San Diego, USA (2004)
- 57.Pardalos, P.M., Resende, G.C.: Handbook of applied optimization. Oxford University Press, N.Y, USA (2002)
- 58.Peeters, L.: Cyclic Railway Timetable Optimization. Ph.D. thesis. ERIM, Rotterdam School of Management, Erasmus University Rotterdam, Netherlands (2003)
- 59.Petersen, E., Taylor, A.: A structured model for rail line simulation and optimization. Transportation Science, Vol. 16, No. 2. (1982) 192-206
- 60.Ping, L., Axin, N., Limin, J., Fuzhang, W.: Study on intelligent train dispatching. IEEE Intelligent Transportation Systems Conference Proceedings. Oakland, USA (2001)
- 61.Pudney, P., Wardrop, A.: Generating train plans with Problem Space Search. Proceedings of the 9th International Conference on Computer-Aided Scheduling of Public Transport (CASPT). San Diego, USA (2004)
- 62.Reeves, C.R. (ed.): Modern heuristic techniques for combinatorial problems. McGraw-Hill, London, UK (1995)
- 63.Şahin, İ.: Railway traffic control and train scheduling based on inter-train conflict management. Transportation Research Part B, Vol. 33. (1999) 511-534
- 64.Şahin, G., Ahuja, R.K., Cunha, C.B.: New approaches for the train dispatching problem. submitted to Transportation Science (2005)
- 65.Salim, V., Cai, X.: A genetic algorithm for railway scheduling with environmental considerations. Environmental Modeling & Software, Vol. 12, No. 4. (1997) 301-309
- 66.Sauder, R., Westerman, W.: Computer aided train dispatching: Decision support through optimization. Interfaces 13. (1983) 24-37
- 67.Schaefer, H., Pferdmenges, S.: An expert system for real-time train dispatching. Computers in Railway (COMPRAIL) 94. Madrid, Spain (1994)
- 68.Shoji, S., Igarashi, A.: New trends of train control and management systems with real-time and non real-time properties. Proceedings for ISADS 97 - the Third International Symposium on Autonomous Decentralized Systems 1997. IEEE Comput. Soc. Press. (1997) 319-326

69. Spzigel, B.: Optimal train scheduling on a single track railway. In: Ross, M. (ed.): OR'72. North Holland Publishing Co. (1973) 343-352
70. Törnquist, J., Persson, J.A.: N-tracked railway traffic re-scheduling during disturbances: theoretical and practical implications. Presented at INFORMS Annual Conference and RASIG session November 13, 2005, San Francisco, USA. Accepted for publication in Transportation Research Part B during 2006 (2005).
71. Vernazza, G., Zunino, R.: A distributed intelligence methodology for railway traffic control. IEEE Transactions on Vehicular Technology, Vol. 39, Issue 3. (1990) 263-270
72. Vieira, P., Neto, L.E., Bessa, E., Gomide, F.: Railway dispatch and control. Proceedings for the 18th International Conference of the North American Fuzzy Information Processing Society (NAFIPS99), New York, USA. (1999) 134-138
73. Wegele, S., Schnieder, E.: Dispatching of train operations using genetic algorithms. Proceedings of the 9th International Conference on Computer-Aided Scheduling of Public Transport (CASPT), San Diego, USA (2004)
74. Wooldridge, M.: An introduction to MultiAgent Systems. John Wiley and Sons Ltd, Chichester, England, UK (2002)
75. Zhou, X., Zhong, M.: Bicriteria train scheduling for high-speed passenger railroad planning applications. European Journal of Operational Research, Vol. 167. (2005) 752-771
76. Zwaneveld, P.J., Kroon, L.G., Romeijn, E.H., Salomon, M., Dauzère-Pérès, S., van Hoesel, S. P.M., Ambergen, H.W.: Routing Trains Through Railway Stations: Model Formulation and Algorithms. Transportation Science 30. (1996) 181-194

Appendix

Table 8. Summary of approaches for tactical scheduling, where each line represents an approach. The first parenthesis in the second column specifies if the approach considers a line (L) or can represent a network (N). The second parenthesis specifies what type of non-station segments that can be handled, i.e. if the segments can have bi-directional (B) tracks or only uni-directional (U) and the maximum number of tracks that are possible for a segment to include; single (S), double (D) or an arbitrary number (N). The third parenthesis specifies in the same way how segments that represent stations may look like. ‘-’ means that information is missing and ‘∞’ means that the capacity (number of tracks) is unrestricted.

Approach	Infrastructure representation	Objective	Solution mechanism	Control	Evaluation level	Problem instance and size
Petersen, Taylor (1982)	(L)(B:BN)(S:BN)	Max performance	Heuristic solving one conflict at a time based on rules/priorities	C	2	Line: 20 segments, 51 trains
Salim, Cai (1997)	(L)(B:BS)(S:B∞)	Min waiting and stopping costs	Determine meets w. GA	C	3	Line: 12 segments, 14 trains
Nilsson (1999), Isacsson, Nilsson (2003)	(L)(B:BS)(S:B∞)	Max profit	Select a feasible combinations of slots via auctions	D	2	Line: 2 stations, 1 block forming 11 slots (markets) and 6 bidders
Blum, Eskandarian (2002a, 2002b)	(L)(B:BS)(S:B∞)	Max profit	Reserve tracks for trains in order of highest profit using MAS and heuristics (GA, critical path analysis)	C	3	Line: 200 segments, 64 trains
Isaai, Singh (2001)	(L)(B:BS)(S:BN)	Min waiting times	Determine the visiting order of trains on stations based on e.g. the earliest time of resource release principle.	C	3	Line: 51 stations, 40 single-, 10 double-tracked segments, 22 trains
Ingolotti et al (2004)	(L)(B:BS,UD)(S:B∞)	Min average traversal time for each new scheduled train	Determine visiting order on segments using a CSP formulation where new trains are added to an existing timetable and each conflicting track request is solved according to priority values and a back-tracking algorithm.	C	3	Line: 65 segments, 81 trains
Lin, Hsu (1994)	(L)(B:BS, UD)(S:BN)	Min delay (of sacrificed train) when solving a local conflict	Start with infeasible schedule and apply a 5-rule-based conflict solver w. earliest-conflict first that shift the slots (i.e. arrival and departure to stations)	C	3	Line: 102 stations, 350 trains
Fukumori (1980)	(L)(B:UD)(S:UN)	Min total weighted delay penalty	Depth-first search branching on train priority to shift departure times from stations allowing overtaking and determine order of trains	C	1	-
Chiang et al. (1998)	(L)(B:BS,UD)(S:BN)	Valid timetable	Repair non-conflict free timetable by set of repair-methods and earliest-first principle to modify overtakes and meets	C	3	Line: 102 stations, 350 trains
Caprara et al (2002)	(L)(B:US)(S:B∞)	Min travel time exceeding ideal run time	Modify train order and overtakes by Lagrangian relaxations and subgradient optimization	H	3	Line: 16 or 48 stations, 221 or 54 trains

Table 9. Continued summary of approaches for tactical scheduling, where each line represents an approach. The first parenthesis in the second column specifies if the approach considers a line (L) or can represent a network (N). The second parenthesis specifies what type of non-station segments that can be handled, i.e. if the segments can have bi-directional (B) tracks or only uni-directional (U) and the maximum number of tracks that are possible for a segment to include; single (S), double (D) or an arbitrary number (N). The third parenthesis specifies in the same way how segments that represent stations may look like. ‘-’ means that information is missing and ‘∞’ means that the capacity (number of tracks) is unrestricted.

Approach	Infrastructure representation	Objective	Solution mechanism	Control	Evaluation level	Problem instance and size
Chang, Chung (2005)	(L)(B:US)(S:US)	Min total time in system, passenger travel times and deviation from initial schedule	Decide visiting order of trains on stations using GA	C	3	Line: 30 stations, 100 trains
Oliviera, Smith (2001)	(N)(B:BN)(S:B-∞)	Min total tardiness	Determine order of trains using B&B and hill climbing	C	3	Line: 14 segments, 49 trains
Brewer, Plott (1996)	(N)(B:BN)(S:B-∞)	Max profit	Select a feasible combinations of slots using auctions	D	2	Line: 2 blocks, 9 train slots, 10 agents
Brännlund et al. (1998)	(N)(B:BN)(S:BN)	Max profit	Allocate discrete time units of segment to trains using Lagrangian relaxations	H	3	Line: 17 stations, 16 BS segments, 26 trains
Ghoseiri et al. (2004)	(N)(B:BN)(S:BN)	Multiple objectives: 1) Min fuel consumption, 2) Min passenger time	Determine visiting order on segments and stations allowing meets and overtakes w. an e-constraint method and distance-based method	C	2	Line: 24 segments, 6 trains
Mackenzie (2000)	(N)(B:BN)(S:BN)	Min weighted tardiness penalty function	Allocate discrete time units of blocks to trains using (1) Lagrangian relaxations, (2) Problem Space Search local search heuristics	H, C	2	Line: 60 segments, 34 trains
Pudney, Wardop (2004)	(N)(B:BN)(S:BN)	Min total lateness cost	Allocate start times at segments by a sorting algorithm and Problem space search perturbing the data	C	3	Network: 35 meet points, 260 trains
Pacciarelli, Pranzo (2001)	(N)(B:BN)(S:BN)	Min total travel time	Decide visiting order of trains on segments and stations using TS	C	3	Network: -
Carey and Lockwood (1995), Carey (1994a-b)	(N)(B:BS)(S:B-∞)	Minimise travel and waiting time costs	Decide visiting order of trains on segments and branching on which train to next path	C	2	Line: 10 stations, 28 segments, 10 trains
Zhou, Zhong (2005)	(N)(B:US)(S:B-∞)	Min interdeparture time, total travel time	Modify overtakes by B&B and Beam search	C	3	Line: 17 segments, 36 trains

Table 10. Summary of approaches for operational scheduling, where each line represents an approach. The first parenthesis in the second column specifies if the approach considers a *line* (L) or can represent a *network* (N). The second parenthesis specifies what type of non-station segments that can be handled, i.e. if the segments can have bi-directional (B) tracks or only uni-directional (U) and the maximum number of tracks that are possible for a segment to include; *single* (S), *double* (D) or an arbitrary number (N). The third parenthesis specifies in the same way how segments that represent stations may look like. ‘-’ means that information is missing and ‘∞’ means that the capacity (number of tracks) is unrestricted.

Approach	Infrastructure representation	Objective	Solution mechanism	Control	Evaluation level	Problem instance and size
Jovanovic (1989)	(L)(B:BS)(S:BD)	Min tardiness costs	Fixating where trains overtake and order of trains in each direction, while deciding where trains in opposite direction meet using B&B incorporating heuristics	C	4	Line: 130 meet points, 200 trains
Cai et.al(1998)	(L)(B:BS)(S:BD)	Min stopping and waiting costs	Modify train order and times on tracks using a Greedy algorithm w. a set of conflict-dependent subroutines	C	2	Line: 10 segments, 99 trains
Sauder, Westerman (1983)	(L)(B:BS)(S:BS)	Trains reach destination within a time interval and min total delay cost	Meet-plan decisions tree constructed by a branching algorithm solving conflicts by arranging meets (one at a time)	C	5	Line:
Higgins et.al (1997)	(L)(B:BS)(S:UD)	Min total weighted travel time	Solve conflicts by set of routines (LS, GA,TS, and hybrids).	C	3	Line: 14 UD stations, 13 US segments, 49 trains.
Dorfman, Medanic (2004)	(N)(B:BN)(S:BN)	Min energy costs	Determine next slot to occupy track resource w. a Greedy heuristic	C	2	Line: 8 segments, 36 trains
Szpigel (1973)	(N)(B:BS)(S:B∞)	Min weighted travel times	Determine visiting order of trains on segments w. various branching procedures	C	2	Line: 5 segments, 10 trains
Kraay and Harker (1995)	(N)(B:BS)(S:B∞)	Min tardiness costs	Column generation to find a bound, Applying local search heuristics to an LP-model (fixating/ignoring) the binary variables specifying where trains meet and overtake.	C	3	Line: 11 meet points, 16 segments

Table 11. Summary of approaches for re-scheduling, where each line represents an approach. The first parenthesis in the second column specifies if the approach considers a *line* (L) or can represent a *network* (N). The second parenthesis specifies what type of non-station segments that can be handled, i.e. if the segments can have bi-directional (B) tracks or only uni-directional (U) and the maximum number of tracks that are possible for a segment to include; *single* (S), *double* (D) or an arbitrary number (N). The third parenthesis specifies in the same way how segments that represent stations may look like. ‘-’ means that information is missing and ‘∞’ means that the capacity (number of tracks) is unrestricted.

Approach	Infrastructure representation	Objective	Solution mechanism	Control	Evaluation level	Problem instance and size
Hellström et.al(1998)	(L)(B:BS)(S:BD)	Min tardiness costs	Fixating where trains overtake and order of trains in each directions, while deciding where trains in opposite direction meet using a B&B procedure	C	3	Line: 23 single-tracked segments, 20 trains
Sahin (1999)	(L)(B:BS)(S:BD)	Min delay of the two local conflict resolutions	Solve each conflict (pair of conflicting track requests) by applying an approximative look-ahead heuristic comparing the effectiveness of the two alternative solutions (delaying train i or train j)	C	2	Line: 19 stations/meet points, 20 trains
Cheng (1998)	(L)(B:UD)(S:BN)	Solve conflicts based on priority	Decide order of use of resources w. priority-based sorting and simulation	C	2	Line: 3 stations, 2 uni-directional double-tracked segments, 8 trains
Chiu et.al. (1996)	(L)(B:BS)(S:BS)	Min largest delay per train	With varying heuristic strategies such as "choose smallest delay change first" the order of trains on segments are modified.	C	3	Line: several stations, BS segments
Ping et.al (2001)	(L)(B:UD)(S:B∞)	Min total delay	Determine visiting orders on segments and start times using GA	C	3	Line: Double-tracked with 14 stations, 250 trains
Komaya, Fukuda (1991)	(L)(B:US)(S:-)	Min total accumulated delay for all trains	Decide order of trains on segment between two ordered stations using an expert system	C	4	Line: 14 stations, 40 trains
Jia, Zhang (1993)	(L)(B:US)(S:US)	Based on priorities	Decide order of trains on stations w. priority-based sorting	L	3	Line: 12 stations, 12 trains
Vernazza, Zunino (1990)	(N)(B:-)(S:-)	Most urgent conflicts dealt with first	Allocate tracks to trains by trains "bidding" the capacity to the local DCs that handles and allocates based on local urgency and priority rules	L	3	Network:
Shoji, Igarashi (1997), Kitahara et.al. (2000)	(N)(B:-)(S:-)	-	-	D	5	Network: 17 lines, 250 stations, 6200 trains
Iyer, Gosh (1995);Lee, Gosh (2001)	(N)(B:-)(S:-)	Each train minimises its total travel time	Each train requests for N tracks ahead and negotiates with resp. infrastructure owner (i.e. stations) to grant or refuse the request	L	3	A network: 50 stations, 84 segments.
Viera et. al. (1999)	(N)(B:B-)(S:B-)	Several objectives	Decide meets and overtakes based on priorities from a fuzzy rule-base	C	4	Line: Single-tracked segments w. 43 sidings.

Table 12. Continued summary of approaches for re-scheduling, where each line represents an approach. The first parenthesis in the second column specifies if the approach considers a *line* (L) or can represent a *network* (N). The second parenthesis specifies what type of non-station segments that can be handled, i.e. if the segments can have bi-directional (B) tracks or only uni-directional (U) and the maximum number of tracks that are possible for a segment to include; *single* (S), *double* (D) or an arbitrary number (N). The third parenthesis specifies in the same way how segments that represent stations may look like. ‘-’ means that information is missing and ‘∞’ means that the capacity (number of tracks) is unrestricted.

Approach	Infrastructure representation	Objective	Solution mechanism	Control	Evaluation level	Problem instance and size
Hellström et.al(1998)	(L)(B:BS)(S:BD)	Min tardiness costs	Fixating where trains overtake and order of trains in each directions, while deciding where trains in opposite direction meet using a B&B procedure	C	3	Line: 23 single-tracked segments, 20 trains
Missikoff (1997)	(N)(B:BN)(S:-)	Min local weighted delay costs	Heuristics (Hillclimbing, A-search) that finds a conflict, solves it locally with respect to the local delay cost and approximative cost for global costs	L	3	Line: double-tracked
Wegele, Schnieder (2004)	(N)(B:BN)(S:BN)	Min passenger annoyance for platforms changes and delays	Determine train visiting times at nodes (signals and switches) using B&B improved by GA	C	3	Network: 104 stations, 1000 trains
Törnquist, Persson (2005)	(N)(B:BN)(S:BN)	Min total delay, min total delay costs	Determine train visiting order on segments using B&B (of IP solver CPLEX)	C	3	Network: 130 stations, 136 segments, 93 trains
Ho, Yeung (2001)	(N)(B:BN)(S:BN)	Min total weighted delay	Decide order of track usage using TS, SA, GA.	C	2	-
Lamma et.al. (1997)	(N)(B:BN)(S:BN)	Min train delays	Local schedulers allocate resources to train by using priority rules	D	3	Line:
Schaefer, Pferdenges (1994)	(N)(B:BN)(S:BN)	Min weighted delays	An expert-system w. rule-based greedy algorithm building a decision-tree w. breadth-first search and primary conflicts on top level	C	3	Line: Single- and double-tracked segments for traffic between 3 and 24-hours
Sahin et.al(2005)	(N)(B:BN)(S:BN)	Min total delay	IP-based heuristics limiting max allowed delay/train, "local" rule-based simulation heuristic, Greedy enumeration heuristic	C	3	Line: 25 stations, 24 single-tracked segments, 25 trains over 24-hours
D'Ariano, Pranzo (2004), Pacchiarelli et.al (2004)	(N)(B:BN)(S:BN)	Min the maximum secondary delay	Create a non-valid timetable, apply a greedy conflict resolution algorithm that chooses high priority conflicts first and solves them according to "most affected train gets priority", finally a pre-processing phase takes over.	C	3	Line: 21 US segments, 4 trains
Koch (2000)	(N)(B:BS)(S:-)	Min total delay cost	A* search	C	4	Line: 23 stations, single-tracked segments, 23 trains
Larrouche et.al.(1996)	(N)(B:UN)(S:-)	Multiple, context-dependent, tacit and subjective objectives	Search for a resource for each train slot using an expert system	C	4	Network: 250 trains