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Sub-problems interaction analysis based three-level decomposition algorithm for real-time train scheduling and routing problems in railway stations

Lijie Bai, Thomas Bourdeaud'huy, Emmanuel Castelain, Qi Zhang

Abstract The management of rail traffic in stations requires careful scheduling to fit to the existing infrastructure, while avoiding conflicts between large numbers of trains and satisfying safety or business policy and objectives. The train scheduling and routing problem studied includes four tasks: scheduling, routing, platforming and conflict resolution. We propose a three-level decomposition method based on the interactional relationship among four tasks mentioned above to enhance the computational efficiency. This method is tested on full-day timetable obtained from the real-world stations.

Keywords Train routing; Train scheduling; Conflict resolution; Decomposition method

1. Introduction

A railway station with complex entering and leaving routes network is a busy system with increasing patterns of train services that require accurate scheduling and routing to adapt to the limited infrastructures. At peak hours, the infrastructure is operated nearly at capacity margins. When unexpected disturbances and disruptions affect the normal course of daily operations, dispatchers need to regenerate a feasible timetable by rerouting, delaying or even cancelling some trains to reduce the propagation of delay.

[1] has developed a real-time dispatching system, called ROMA, to automatically recover disturbances. ROMA is able to automatically control traffic, evaluating the detailed effects of train reordering [2] and local re-routing [3] actions, while taking into account minimum distance headway between consecutive trains and the corresponding variability of train dynamics[4][5][6]. [7] focus on the real-time CDR (Conflict Detection and Resolution) problem through junctions and proposes a constraint programming formulation for the combined routing and sequencing

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problem. [8] develop two new routing neighborhoods of different size in order to search for more effective routings, and study their structural properties in a tabu search scheme. [9] and [10] treat train platforming problem considered for the case of multiple routes where platform times can vary in a discrete interval. [11] propose an Integer Linear Programming model (ILP) for the TTP in railway node. This paper studies the scheduling and routing problem at an operational level faced by railway station managers to generate a conflict-free non-cyclic timetable which consists of two sets of circulations. One set is made of commercial circulations given by regional levels. The other set corresponds to technical circulations (shunting) added by the railway station managers to prepare or repair the trains. The problem that we address in this paper is NP-hard and can be stated as follows. Given the layout of a railway station, arrival and departure times, as well as the destination and origin of trains, we aim to schedule the technical circulations within the allowable deviations and to route as many as possible trains through the station. The blocking trains should be pointed out if a solution for all trains cannot be found. The solution must ensure that no pair of trains is conflicting over routes and tracks, while allowing the coupling and uncoupling of trains at tracks and respecting their preferences of platforms.

To solve our problem, we update the timetable under rolling-horizon framework to adapt the dynamic railway traffic, as stated in our previous article [12]. To complete the update calculation in short time, we propose sub-problems interaction analysis based three-level decomposition algorithm.

2. Problem formalization

In this section, we firstly formalize our scheduling and routing problem in station. After the description of three-level operational mechanism, we focus on the detailed mathematical model of three levels. A railway station contains a set L^e of lines located outside the home signals at the entrance of the station, a set L^i of lines next to the platforms and a set of switches. A route $p \in P^{(l^i, l^e)}$ contains a set of ordered switches $p = [s_1^p, s_2^p, \dots, s_{|p|}^p]$ which connects a platform line l^i with a section line l^e . The traffic in the railway station is defined by a set of trains T . Every train t contains a set of ordered movements $M^t = [m_1^t, m_2^t, \dots, m_{|M^t|}^t] \subset M$. The index of a movement represents its chronological order, for example m_1^t occurs before m_2^t .

Table 1. Movements classification

	Commercial	Technical
Leaving	M^{CL}	M^{TL}
Entering	M^{CE}	M^{TE}

Four types of movements are defined depending on their commercial or technical nature and their direction as shown in Table 1. The set of movements M is divided thus into four subsets such that $M = M^{CL} \cup M^{TL} \cup M^{CE} \cup M^{TE}$.

A train t contains at least two movements $[m_1^t, m_2^t]$: one entering movement (from section line to platform line) and one leaving movement (from platform line to section line). The reference arrival and departure times of trains, given by administrative levels and station manager, are represented by reference starting and ending times of their movements $[\alpha_m^{ref}, \beta_m^{ref}]$. While ensuring the minimum operational time on tracks implicitly given by the ideal timetable, a deviation interval L^{dev} is permitted for the technical circulations depending on the direction. The relationship between the reference time and flexible adjustment time interval $[\alpha_m^{flex}, \beta_m^{flex}]$ is resumed in the Table 2.

Table 2. Flexible adjustment time interval of movements

Type of movements	α_m^{flex}	β_m^{flex}
$M^{CL} \cup M^{CE}$	α_m^{ref}	β_m^{ref}
M^{TL}	α_m^{ref}	$\beta_m^{ref} + L^{dev}$
M^{TE}	$\alpha_m^{ref} - L^{dev}$	β_m^{ref}

Speed variation dynamics of trains running in stations is not taken into account. Occupation of routing resources is detailed in Fig 1. The route occupied is locked until the train leaves the last switch of the route $[\alpha_m, \beta_m]$. Route locking time is fixed as S according to the dispatcher's suggestions. The track reserved is locked from the train entering the station until the track totally released $[A_t, B_t]$.

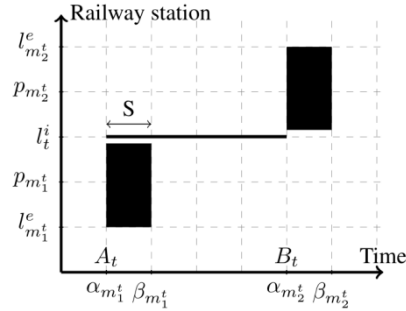


Fig 1. Occupation of routing resources

In our problem, the coupling and uncoupling operations of trains at tracks are taken into account. The choice of tracks for trains depends on the trains' characters, passenger service and usual practices in stations. We provide a set of tracks L_t^{Pref} in priority order for each train which combines the length compatibility and the direction preference.

The ideal timetables, including reference times and section lines, are generally conflicting, while we struggle to route all trains through the station. In order to resolve these conflicts, we are allowed to modify (anticipate or delay) the technical movements within flexible adjustment time interval $[\alpha_m^{flex}, \beta_m^{flex}]$ to alleviate the conflicts on paths, but it causes the increase of stopping time at tracks. In some complex and busy stations, a conflict-free timetable is not guaranteed. So trains

cancellation is permitted, ensuring that a feasible solution is always obtained. The objective function is to minimize the number of trains cancelled.

3. Three-level decomposition algorithm

The problem described in our paper consists of three parts of decision: scheduling, routing and cancellation. The cancellation decision is supported by both scheduling and routing decisions. A wise combination of scheduling and routing decisions can efficaciously reduce the number of trains cancelled. However the combination of scheduling and routing decisions represents a huge solutions search space. In order to reduce the calculation complexity, we divide the problem into two parts: scheduling-cancellation sub-problem and routing-cancellation sub-problem, so as to avoid the huge amount of combinations between scheduling and routing variables. At the same time, the correlation between the two sub-problems cannot be ignored. In this case, a three-level decomposition method is designed as a circle mechanism to satisfy the demand of independence and cooperation between scheduling and routing in the resolution process. Level I solve the routing-cancellation sub-problem with the given scheduling decision. Level II is responsible for the smooth cooperation between the two sub-problems. Succeeding the given scheduling decision and the cancellation decision solved in Level I, Level II re-route the trains to maximize the margin of scheduling decisions for trains cancelled in Level I. Level III succeeds the routing decision solved in Level II and re-schedule the trains to minimize the number of trains cancelled.

Three-level decomposition method simplifies the whole problem by three ways. Firstly, the huge amount of combinations between scheduling and routing decisions are avoided. In each sub-problem, the solution search space is narrowed. Secondly, the cooperation relationship between routing and scheduling is recovered by Level II which try to re-route trains and movements with the cancellation decision solved in Level I, so as to maximize the scheduling margin for Level III. Finally, the original cancellation is identified in Level I. We distinguish the cancellation into two types according to the causes: original cancellation and operational cancellation. The original cancellation brought by ideal timetable is caused by the unavoidable conflicting stops on tracks among trains or the overload of commercial movements on station networks. Note that only the actual time of technical movements can be modified in scheduling sub-problem. In the ideal timetable, the duration of stop on tracks is minimal for all trains. In the following steps, modification of actual time for technical movements make the trains' stopping on tracks prolonged and the conflicts on tracks intensified. So at the first iteration, level I has the best chance to allocate tracks and paths separately to trains' stopping and commercial movements with the ideal timetable as parameters. Moreover, the weighted function of Level I prefer to cancel technical movements. Under all these favorable conditions, the original cancellation is identified by Lev-

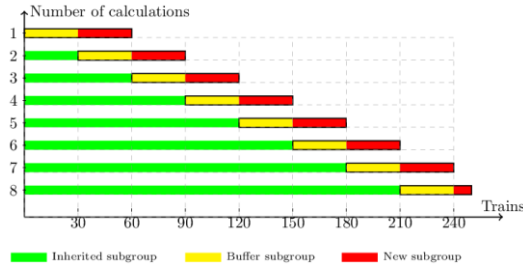
el I at the first iteration and unrecoverable in the following steps. The operational cancellation is caused by the infeasible technical movements. It is possible to absorb the operational cancellation through the following iterations.

4. Experiments and Results

To observe the performance of three-level decomposition algorithm, we solve a full-day timetable in a real-world station in two ways. Firstly, we solve the full-day problem step by step under rolling-horizon framework. In each calculation, the solution obtained by three-level method is provided as an initial solution to the exact method described in our previous article [12]. Maximum iteration of three-level method is 5. Solutions obtained with and without three-level method are compared in Table 3. Secondly, we execute one calculation of three-level method to solve the full-day problem. Maximum iteration of three-level method is 9.

The computational results are obtained by using CPLEX version 12.6 on a 64 bits computer under Linux with Intel i5-2520M CPU at 2.5GHz and 8GB memory RAM. The calculation time is limited to 500 seconds.

A brief introduction of rolling-horizon framework designed in [12] is as follows. The full-day problem of 247 trains is updated by 8 calculations in chronological sequence. An illustrative execution is given in Fig 2. In each calculation, we solve



a problem of 60 trains (one yellow buffer subgroup and one red new subgroup) and take the solution of green inherited subgroup as valid constraints. Inherited subgroup includes the buffer subgroup solved in the last calculation and the trains have already passed through the station.

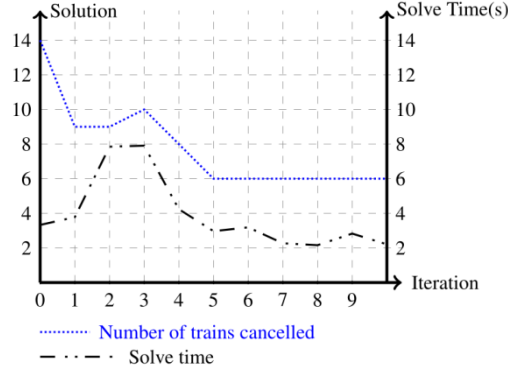
Fig.2 Rolling-horizon framework.

The one-day timetable is divided into 8 subgroups of trains shown in the first column. The second and third column contains the numbers of technical and commercial movements for the relevant subgroup. The train subgroup can be divided into three groups: inherited group, fixed group and buffer group which are described, in the 5th and 6th columns, by the number of trains and the time interval occupied in minutes. With $N = 60$, there is no intersection between the time interval of buffer group and the time interval of inherited group to avoid insolvable potential conflicts with inherited group. The minimum number of trains cancelled solved within 500 seconds and the resolution information are shown in the last two large columns in Table 3. We can see that three-level method greatly reduces

the solve time from 2496s to 83s. At the same time, comparison of solution gap states clearly that three-level decomposition algorithm efficiently improve the quality of solution to optimality as the gap is reduced to 0%. With three-level method, 6 trains, instead of 9 trains, are cancelled in the full-day timetable.

Table 3. Recovery of full-day timetable under rolling-horizon framework

Trains Subgroup	Movements		Group Type	Trains	Time Interval(min)	TiLim=500s with tri-level			TiLim=500s without tri-level		
	Tech.	Comm.				Obj	GAP	Solve time	Obj	GAP	Solve time
0-59	45	78	Inherited	-	-	0	0.00%	1.56	0	0.00%	50.23
			Buffer	0-29	30-406						
			New	30-59	322-530						
30-89	41	78	Inherited	0-29	30-406	2	0.00%	48.42	2	100.00%	500.05
			Buffer	30-59	322-530						
			New	60-89	438-662						
60-119	48	73	Inherited	0-59	30-530	4	0.00%	2.15	7	85.71%	500.07
			Buffer	60-89	438-662						
			New	90-119	575-795						
90-149	47	76	Inherited	0-89	30-662	4	0.00%	2.06	7	33.33%	500.02
			Buffer	90-119	575-795						
			New	120-149	735-967						
120-179	40	84	Inherited	0-119	30-795	4	0.00%	7.65	7	0.00%	165.09
			Buffer	120-149	735-967						
			New	150-179	892-1133						
150-209	31	92	Inherited	0-149	30-967	5	0.00%	7.42	8	25.00%	500.04
			Buffer	150-179	892-1133						
			New	180-209	1012-1208						
180-239	32	89	Inherited	0-179	30-1133	6	0.00%	9.2	9	12.50%	275.81
			Buffer	180-209	1012-1208						
			New	210-239	1143-1361						
210-246	22	53	Inherited	0-209	30-1208	6	0.00%	4.26	9	9.37%	6.10
			Buffer	210-239	1143-1361						
			New	240-246	1215-1494						



Then we execute one calculation of three-level method to solve the full-day timetable. The solution is displayed in Fig 3. The best solution found at the 5th iteration is 6 trains cancelled. The total solve time is 30s shorter than 83s.

Fig 3. Recovery of full-day timetable by three-level method

5. Conclusion

In this paper, we present the train scheduling and routing problem through a railway station. To ensure the feasibility of timetable, cancellation of trains is permitted to eliminate insolvable conflicts. The timetable adapts the dynamic railway traffic under the rolling horizon framework. Three-level decomposition algorithm based on sub-problems interaction analysis efficiently improves the per-

formance of adapting timetable in railway stations. The complete algorithm can be easily applied on different railway stations.

In further work, more real cases in different railway stations will be collected and studied to evaluate the efficiency of the complete algorithm.

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