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A PRELIMINARY DEVELOPMENT OF MATHEMATICAL MODEL FOR TRAIN RESCHEDULING

Zuraida Alwadood¹, Adibah Shuib² and Norlida Abd. Hamid³

¹,²Faculty of Computer and Mathematical Sciences, UiTM Shah Alam, Selangor, Malaysia
³Arshad Ayub Graduate Business School, UiTM Shah Alam, Selangor, Malaysia
{zuraida794, adibah253, norlida054}@salam.uitm.edu.my

Abstract

Mathematical optimization techniques have been widely used in modelling and solving rail transportation problem. In dealing with conflicting trains during service disruptions, rescheduling train timetable aims to produce an adjusted periodic timetable for the affected trains using available resources while satisfying a set of operational constraints. In this paper, we present the preliminary works in the development of a mixed integer programming (MIP) model with the objective to minimize the service delays experienced by passengers when service disruptions occur. An MIP model has the ability to address the highly combinatorial problem and highly interlinked nature of the rail traffic system. Based on a selected reference model, the sets, parameters and the decision variables of the new model are thoroughly discussed in this paper. The working database is concisely illustrated and complexity of the model is also highlighted.

Keywords: Mathematical model, mixed integer programming, service delays, railway rescheduling, mathematical optimization

1. Introduction

Operational problems and unexpected events such as technical failures, equipment breakdown, extraordinary passenger volumes, track accidents or weather conditions normally cause disruptions to railway network. In this situation, control managers need to reshuffle train orders, make unplanned stops and break connections, re-route trains and even delay or cancel scheduled services. Changes in the original train departure and arrival schedules can create conflicts in the use of tracks and platforms. Thus, operational decisions must resolve the problem and reschedule the affected train movement with an objective to minimize the effect of railway traffic perturbations.

This paper intends to present the preliminary works in the development of a mathematical model for solving post-disruption railway rescheduling problem that minimizes the total delays of trains in the whole railway network. To achieve the objective, a mixed integer programming (MIP) model for rescheduling railway will be proposed. The main feature of this paper is the demonstration of the implementation steps concerning the crucial elements for the model construction. It is also expected to highlight the future direction of the modeling works. The complete model and the solution approach are expected to bring new ideas for multiple perspective improvement in delay management, as well as business engineering process and quality engineering improvement.

This paper is outlined as follows: Section 2 discusses some relevant literatures on the railway rescheduling model construction. The mathematical notations that are based on a reference model are explained in Section 3, while Section 4 presents the preliminary works in the mathematical modeling construction. Section 5 highlights the complexity of the model concerning the formulation of complicated combinatorial problem. Section 6 briefly outlines the upcoming tasks to be carried on, specifically the completion of the model and the mathematical solution approaches. The conclusion and final remark of the study is drawn in Section 7.
2. Related works

Among the various types of quantitative models used in rescheduling railway services, a study done by Alwadood et al. (2013) has shown that integer programming (IP) and MIP are widely used in formulating the optimization problem. They are technically chosen because the models are able to accommodate the linearity of the objective functions and constraints.

Table 1. Cross analysis of sets, parameters and decision variables used in models of related works

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This section summarizes and compares the criteria that are relevant in the formulation of the mathematical models which are used in selected literatures of train rescheduling problem. Among the published results are the works of Narayanaswami and Rangaraj (2013), Caimi et al. (2012), Acuna-Agost (2010), Stanojevic et al. (2010), Murali (2010), Afonso (2008), Zhou and Zhong (2007), Tornquist and Persson (2007) and Tornquist and Persson (2005).

Basically, the mathematical models are based on three sets namely train, block or segment and station, as shown explicitly in Table 1(A). The set of trains contains all types of train running on the rail track which may be in outbound or inbound direction, or in some works it is known as up line or down line direction. The set of blocks or segments is the collection of all sections of railway tracks which can only be occupied by one train in a direction, at any particular time. A train is disallowed to enter an empty block section without first securing the permission of the station. The set of stations is the entire terminal meet point for the trains within the relevant area of study. These three sets are dominant in all the models by the nine selected literatures. However the sets of events for each of these train, block or segment and station are only used in some of the studies. These sets of events are the resource requested by a specific train, block or segments and station, respectively.

Due to the dimensions of the problem and the complex nature of the IP and MIP models, the selection of the parameters that would be taken into the model formulation needs to be closely examined. Table 1(B) provides the cross analysis of some common main model parameters used in the selected research works. Many selected models share almost similar parameters but there are also models which incorporate a set of unique parameters as an attempt to improve an existing model or to introduce a hybrid mathematical model. For instance, Tornquist and Persson (2005) introduced the parameters for train connection in order to handle the objective function of costs for missing connections. In addition to this, Acuna Agost (2010) introduced the parameters of braking and accelerating time as a result of unplanned stops. Having said this, to come up with a newly-developed model, it is recommended that the common listed parameters should be first included to ensure the sensibility of the model. This will then be followed by introducing fresh elements in the model formulation to offer a unique research novelty.

As all the research works aim to arrive at provisional timetables which are able to minimize service delay, then it is expected that the most important decision variables in the model formulation should be the start time and end time of the event for train. Other decision variables relate to which train that is to be used, which track the train should run on, which station the train should be leaving from or waiting at, among others. For the decision variables involving ‘yes’ or ‘no’ answer, binary variables of ‘1’ and ‘0’ are used. The cross analysis of decision variables used in the mathematical programming models in the selected literatures is shown in Table 1(C).

3. The reference model

Train rescheduling is a large size combinatorial problem. In many countries nowadays, the railway infrastructure is no longer operating on an isolated or separate railway tracks but rather involving high integration of rail network which consists of many interact railway lines. A cross analysis on the sets, parameters and decision variables that have been used in various mathematical models is done by Alwadood et al. (2012). Among all the models analyzed, Tornquist and Persson (2007) model is selected to be the reference model for this work.

Tornquist and Persson (2007) has developed an MIP model that aims to minimize the total final delay of the railway traffic and the total cost associated with delays. It is a strong formulation of rescheduling railway traffic problem in railway network because it accommodates the concept of multi-operator tracked lines, multi-passenger demands and highly interacting traffic. Other mathematical and non-mathematical models did not address
these complexities in the model formulation. Therefore, the model will be chosen as the reference model in this study.

Besides the strength of this model, few aspects are disregarded in the model formulation which may affect the practicality of the generated outcomes. For instance, due to the limited availability of data, all stations in the experimented rail network are assumed to have four parallel tracks. The assumption may be an oversimplification as stations could have far greater number of parallel tracks or only a minimum number of two tracks for smaller stations.

Other flaw of the model is due to a constraint which indicates that two trains must be separated by certain time duration when they are on the same track of a segment. In practice, two trains using different tracks on different segments must also be separated by certain gap of time. For example, suppose two trains using different tracks on different segments are going to cross each other and heading to the other track of the subsequent segments. Even these two trains are using different tracks of a segment, the action can still violate the rail safety restrictions and may possibly cause an accident. To cater the conflicting routing, the signalling switches between the tracks need to be included in the model formulation, so as to coordinate each event in a synchronized sequence and avoid accidents.

Based on the work done by Alwadood et al. (2012), the new mathematical model to be formulated will largely be using notation from Tornquist and Persson model, in addition to a few parameters from other literatures including Stanojevic et al. (2010), Murali (2010) and Afonso (2008). Hence some of the notations used for the preliminary model’s sets, parameters and decision variables will be the same.

A. Sets and parameters

Basically, the model is based on three sets. The first set is the set of trains $T$ with index $i$, where $i \in T$ contains all train running on the rail track, which may be in up line or down line direction. The parameter $g_{train}^i$ denotes the length of train $i$.

The second set is the set of segment $B$ with index $j$, where $j \in B$ is the collection of all sections of railway tracks, which are separated by the series of signal switch control. An ordinary train route has a signal switch control located right before the block entrance. Once accepted, no other trains will be allowed on the block or segment without permission from the signal switch. The distance between the signals varies along the track based on the geographical safety aspects such as the elevation of ground and the blind spots at curving turn.

There are two types of segment namely segment between stations and segment within stations which are denoted by $s_j = 1$ and $s_j = 0$, respectively. Figure 1 illustrates the segment between stations (B, C and D) and the segment within stations (A and E). For each segment, there is a set of parallel tracks $P_j = \{1, \ldots, p_j\}$ and the parameter $g_{track}^j$ denotes the length of each track $t$ of segment $j$. A standard railway safety regulation normally imposes a minimum distance between two consecutive trains to avoid
accidents. The distance which is usually termed as time headway, indicates the time when a train exits from a segment and the subsequent train enters the same segment. The parameter $A_j$ denotes the time headway in a case when one train is following the other on a track of segment $j$.

Finally, the third set is the set of events $E$ with index $k$, where $k \in E$ are the resource request by a specific train for a specific block. $K_i \subseteq E$ is the ordered set of events of train $i$, and $L_j \subseteq E$ is the ordered set of events of segment $j$, as established in the original timetable.

Let $o_k$ be the direction of event $k$, having the value of ‘1’ if it is in up line direction and ‘0’ if it is in down line direction. For an event $k$ running at segment between stations, the minimum time is denoted by the parameter $d_k$, which starts when the first train coach enters the segment. The running time largely depends on the train speed profile, including the rates of acceleration and braking when approaching signalling aspects or scheduled stop. On the other hand, an event $k$ waiting at segment within stations, the minimum waiting time is denoted by the parameter $h_k$. A train timetable defines the planned arrival and departure times to satisfy passengers’ demand in reaching their destinations. The parameter $b_{\text{initial}}^k$ and $e_{\text{initial}}^k$ specify the initial start and end of event $k$ as in timetable, respectively. In spite of the schedule established, in real situation, some events do not start and end as time planned. As a real-time train rescheduling needs to cope this instantaneous deviation, $b_{\text{static}}^k$ and $e_{\text{static}}^k$ will denote the real start and real end time of event $k$ in the model.

When stopping at stations, a train must not arrive later than its scheduled arrival time and it must not depart before its scheduled departure time. This is to ensure that passengers are allowed to alight from, and board into, the train safely, with no passengers being left behind. This scheduled stopping time of train $i$ is called dwell time, denoted as $s_j$. A segment station has as small as two platforms, while the larger stations may have up to six platforms. The capacity of each segment station depends on the number of platforms it has. The parameter $m_j$ will denote the capacity of segment station $j$ while $n_j$ is the number of trains at the segment station. Finally $M$ is a large positive constant, given as the largest considered time horizon in minutes.

B. Decision variables

The mathematical programming model aims to come up with a provisional timetable when disruption occurs. There are five decision variables anticipated from the solution method. $x_{\text{begin}}^k$ and $x_{\text{end}}^k$ are the start time and the end time of actual rescheduled event $k$, respectively where $k \in E$, $K_i \subseteq E$ and $L_j \subseteq E$. As a result of the new schedule, the amount of delay that will turn out from the rescheduling event $k$ where $k \in E$ will be denoted by $z_k$. The variable $q_{kt}$ specifies if event $k$ uses track $t$ or otherwise.

Suppose $\hat{k}$ becomes any event following event $k$. When disruption occurs, sometimes the order of the events remains unchanged. However in some cases that usually involve larger disruption, event $k$ may need to be rescheduled to occur after the event $\hat{k}$. In order to distinguish these two outcomes, $\gamma_{kk}$ and $\lambda_{kk}$ are the binary decision variables to denote the former and latter decision variables respectively and $k, \hat{k} \in L_j, j \in B, k < \hat{k}$.
4. The new model

From the original train schedules and the location of the signaling switches along the rail track, the data of time and segment is extracted to form a new diagram (see Figure 2) which shows part of the movement of 11 running trains between 20 segments.

![Diagram showing train location at given time and segment](image)

Figure 2. Train location at given time and segment

The top horizontal row represents the stations with their km locations stated underneath. Each square represents a single segment. Referring to Figure 1, among the segments within station defined earlier can be represented here by Station 4, Station 5 and Station 6 whereas the segment between stations is shown here by the single square between Station 5 and Station 6.

The left most column represents the time for each minute. The enlargement snapshot in the middle of the figure shows that Train 1 is moving towards the right which indicates a down line direction. On the contrary, the shifting of Train 3 to the left side shows that it is moving in the up line direction. Both trains meet each other at a station as their positions stand still for a few minutes at a particular segment.

The raw data obtained from a railway company in Malaysia has been used to serve as a sample data for the purpose of model testing. The railway line connecting some major cities in the Klang Valley of Malaysia is presented in Figure 3. All the data for the parameters has been entered into Excel Worksheet, according to the sequence of events.

![Diagram showing rail network for a train services in the Klang Valley of Malaysia](image)

Figure 3. Rail network for a train services in the Klang Valley of Malaysia
The database in Figure 4 shows some of the parameters needed in the mathematical model construction. All the values are keyed-in based on the data of time and segment from Figure 2.

As every event is associated with a train and a segment, the first two columns present the pairings of train event $K_i$ and segment event $L_j$ according to the original timetable. The sequence is arranged based on time of event, leading by the lower segment number. In the case when two opposite direction events coincide at the same time and segment, then the event in the up line direction will be given the priority to be presented first.

The next four columns show the scheduled initial start and end time, $b_{\text{initial}}^{\text{static}}$ and $e_{\text{initial}}^{\text{static}}$ followed by the real start and end time for each event $b_{k}^{\text{static}}$ and $e_{k}^{\text{static}}$. The rest of the database depicts the data for the model parameter such as segment types, running or waiting time, capacity of station and others.

The novelty of the new model proposed by this study will include the introduction of some new features which include:

- a different number of parallel tracks at stations,
- restrictions posed by signalling switches between tracks, and
- an additional new objective function that aims at maximizing service punctuality rather than minimization of cost.

5. Complexity of the model

Railway rescheduling involves real-time alteration of train schedules in a railway network which is highly interconnected. Mathematically, this is considered as a difficult, combinatorial and strongly constrained problem. The model’s constraints require a large number of hard (operational) constraints and soft (desirability) constraints and the complexity of problem increases with the number of decision variables and constraints. Modelling and solving this railway rescheduling problem is thus considered a highly complex task and an NP-hard problem.

Train rescheduling model needs to be run at macro level of railway networks so as to meet the real-world application demands. The routing and scheduling tasks are very challenging because it normally involves large combinatorial optimization problems. In the early stage, it demands the ability to formulate the real problem into a mathematical representation, incorporating all the factors influencing the decision variables, not forgetting the constraints and uncertainties governing the problem. In later stage, it demands the ability to solve the problem and generate the feasible or optimal solution within a short time frame, using search method or exact method, whichever suits the model.
The algorithm intends to solve railway traffic conflict as fast as possible so as to assist the dispatcher in the resolution process. Solution to conflicts may involve many combinations of stations, departure and arrival times, direction of routes and location of conflicts, especially when the disruption involves a train that interferes with other trains. Therefore, depending on the chosen solution for a conflict, optimal solutions are normally unattainable in large-scale and complex instances, besides the number of feasible solutions can be very large.

6. Next steps

Now that the model’s sets, parameters and decision variables are clearly defined, the next step is to add the novelties to the model constraint. The restriction posed by the novelties spelled out in Section 4 will represent a new set of constraints, in addition to the constraints established by Tornquist and Perrson (2007) and other selected literatures.

A preliminary data collection carried out at the early stage of this research has found out that delays at station and signalling problems are the most crucial causes of delays. A large portion of the delays recorded durations of less than 15 minutes. In addition to this, trains are required to give way to the Electric Train System (ETS) due to its priority.

Next, the study will proceed by testing the proposed model using four rescheduling problem cases for delays of less than 15 minutes, as the following:

Case 1: Delay at station
Case 2: Delay at station involving route clash with an ETS.
Case 3: Signalling problem
Case 4: Signalling problem involving route clash with an ETS.

Heuristic computational methods using AMPL programming language and CPLEX Solver will be implemented. The model is intended to produce quantifiable quick solution to the real-time rescheduling problem and offer service recovery strategies which help the railways services to maintain as an efficient and reliable mode of transportation.

7. Conclusion and further research

This paper presented the preliminary works in the development of a mathematical model that minimizes the total delays of trains in a railway network. An MIP model for rescheduling is chosen to be the tool in finding the optimal solution. By means of a base model, the main elements supporting the model construction are discussed in detail, with the novelty of model yet to be included. In this sense, the paper is expected to assist researchers to formulate structured models by means of the clear definition of model variables and parameters.

The work is part of the study that will be conducted on train rescheduling model to cope with the railway service disruptions within Malaysia commuter rail system. Upon developing a hybrid mathematical model that could minimize service delays for the passenger trains, the solution approaches to the mathematical model will then be proposed to the railway operator. These new model and solution approaches will be presented in next research papers of our study.

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