GROSTLOG 2020
Global Research on Sustainable Transport & Logistics

ISSN: 2622-5778 (online)
Advances in Transportation and Logistics Research
http://proceedings.itltrisakti.ac.id/index.php/altr

HEADWAY ORDER SCHEME (HOS) HEURISTIC FOR THE RAILWAY RESCHEDULING OPTIMIZATION

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Abstract. Railway rescheduling is a critical operation in delay management of passenger railway services. Most past studies related to railway rescheduling have put greater emphasis on how to minimize service delays when service is disrupted. This paper presents a novel Headway and Order Scheme (HOS) heuristic to handle the conflict imposed by railway disruption by means of headway condition and reordering by priority in solving an optimization model for the railway rescheduling. The formulated multi-objective mathematical programming model aims at determining the adjusted schedules for trains based on some priority rules based on train category. The optimization model comprises of two objective functions which are, to minimize the sum of trains delay times and to maximize the reliability of services provided.Computational experiments focuses on Komuter trains rescheduling problems involving various trains priorities settings on Malaysian double track railways in which disruption incidences were mainly due to signaling switches problem and lasts bertween five to 15 inutes. The proposed model was solved using the preemptive goal programming approach. Results show that the model can generate the provisional timetable in 36 seconds and demonstrate that the priority order assigned to trains influenced the model's obhective functions values. For five or 10 minutes duration of disruption, the model's results indicated an average of 20 minutes delay and 88.9% service reliability. The solutions obtained also satisfied all local rail operator's restrictions.

Keywords: Railway rescheduling, komuter trains, heuristic, Head Order Scheme, Mixed Integer Programming, Goal Programming, total delay time, service reliability.

Introduction

Disruptions on rail transportation services may result from unusual passenger volume, rolling stock breakdown, infrastructure failure, power shortages, accident or weather-bound situation and often due to signalling system failures, which cause disruption on segment(s) of the railway network. A disruption causes trains conflict where one or more system constraints are violated and railway or trains rescheduling involves detecting conflicts and applying rescheduling tactics to obtain feasible timetable (Josyula, 2019). Railway rescheduling is an NP-hard problem (Min et al., 2011) and complex from practical and computational perspectives. Nevertheless, some train dispatchers solve it according to experiences and SOPs where timetable adjustment is done manually (Xu et al., 2016; Yin et al., 2017).

For busy railway network, intricacy in finding solution within short time is humongous and absent of systematic approach causes rescheduling process to take longer time and rail service delay prolong. With high demand and departure frequencies, increasing train operations and services, and enormous infrastructure, it is widely agreed that decision support systems are crucial for railway rescheduling (Pellegrini et al., 2019; Samà et al., 2018; Gao et al., 2017). According to Gao et al. (2017), rescheduling problem on railway systems involves macro methods, where infrastructure is described based on groups of block-sections, and micro methods that define infrastructure based on single block-sections. Macro methods consider ideal or constant speed and optimize train operations at stations while micro include speed profiles and train movements in the whole network, thus with a lot of details (Hangfei et al., 2018) making it harder to solve within reasonable computation time.

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Mathematical programming models have been employed by past studies in solving railway rescheduling problems. Tornquist and Persson (2007) use MILP model to solve railway traffic rescheduling of Sweden railway network. Fekete et al. (2011) formulated an IP model to achieve the maximum number of recovered trips and produced dispatching timetable for rescheduling of trips and vehicle circulations for Vienna subway line while Binder et al. (2017) proposed IP model to solve railway rescheduling problem for Dutch railway network. Wang et al. (2019) proposed an MIP model while Zhan et al. (2016) formulated three MILP models to reschedule trains on the same double-track Beijing-Shanghai high speed railway. Solution methods for mathematical programming models can be either exact method where optimal solution is guaranteed, or heuristic method which produces good-enough solution within reasonable time and metaheuristic that describes an iterative master process that coordinates operations of subordinate heuristics to efficiently produce high-quality near-optimal solutions. Fekete et al. (2011) used Branch & Cut, (exact algorithm), Binder et al. (2017) and Pellegrini et al. (2019) used heuristic methods while Tornquist and Persson (2007) applied B&B and Tabu Search. Genetic Algorithm (GA) was used by Hangfei et al. (2018) while Wang et al. (2019) used GA and Particle Swarm Optimization.

Review on past studies mathematical programming models for railway rescheduling indicates that none has considered optimizing service reliability. Thus, our study proposed a mixed integer optimization model with multi-objectives to minimize the sum of trains delay times and to maximize reliability of services. Network topology displaying the interconnectedness of operations in handling disruption and railway rescheduling was established. Headway and Order Scheme (HOS) heuristic was then proposed by recognizing the new block-oriented headway restriction and prioritizing conflict trains to satisfy constraints specified by service operator.

Method

This study focuses on solving rescheduling problem of urban Komuter system under Keretapi Tanah Melayu Berhad (KTMB), which is local railway service provider of Electric Train Service (ETS), Intercity and cargo train services. The railway has multi-track lines with Komuter service sharing the bi-directional rail tracks (BDRT) with ETS while the single-track lines are shared by intercity services and heavy cargo trains. For BDRT, signal facilities are available at all block entrances along the tracks in both directions. Railway rescheduling involves only existing trains. and no trains reroute or service cancellation is allowed. Komuter train has to give way to ETS as necessary thus its rescheduling is subjected to restriction posed by ETS train. The railway interlinks of Rawang-Sg. Gadut and Port Klang-Batu Caves are considered in this study. This Klang Valley Double Track (KDVT) system has 25 train stations, 120 service trips and 67 track segments.

The railway network topology (Figure 1) was established to serve as interactive guide that easily explains the resources, operations, SOP, policy and management concerning the railway system by concentrating on four functions. Items in planning should be finalized before a train starts its trip (1). Normal operations are denoted by black arrows to indicate closely monitored via control panel at Control Centre (2) and end up at train stations (3a). Red arrows denotes disruptions that needs to follow the Standard Disruption Action Procedure (3b). Once a train recovers, it may continue its journey. Otherwise, it will be sent to repair depot. Operation and management team is responsible to analyze service logs reports (4). This railway network topology is a part of an interface for railway rescheduling.

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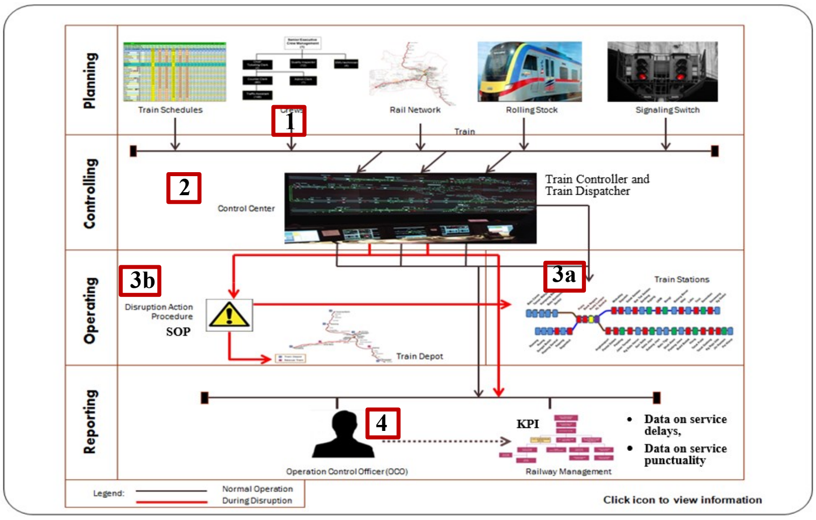

Figure 1: Railway Network Topology

<u>MIGP Model Formulation</u>:

The sets and indices for the model are as the following: T denotes set of trains, $T = \{1, 2, \ldots, u\}$, where u is number of trains and index of train is denoted as i, $i = 1, 2, \ldots, u$, $i \epsilon T$. $K_i^{f_i}$ represents set of i train events, f_i is segment that train i passes by. $B = \{1,2,..,v\}$ represents set of segments, where v is total number of segments, has index $j = 1,2,..,v$, $j \epsilon B$. $L_j^{g_j}$ denotes set of j segment events with g_j being trains that pass segment j. E is a set of events, $E = K_i^{f_i} \cup L_j^{g_j} = \{E_k\}_{k=1}^{q} = \{1, 2, \ldots, q\}$, $i = 1, 2, \ldots, u$, $j = 1, 2, \ldots, v$ and $E = 1$ denotes $E_1, \ldots, E = q$ denotes E_q, q represents number of possible events. k denotes event in K_i and L_j, $k = 1, 2, \ldots, q$, thus either $k \epsilon K_i^{f_i}$, $k \epsilon L_j^{g_j}$ or $k \epsilon E$. $\hat{k}$ represents succesor for event k, based on original timetable where $\hat{k}$, denotes an event (of other train / segment). When service disruption has been solved and trains journey continue, k and $\hat{k}$ events encounter conflict. The HOS heuristic will guide in deciding the order or sequence according to priority such that $k < \hat{k}$.

Railway rescheduling problem can be described as given set of trains, the railway line, original timetable of trains indicating departure-arrival times and tracks assignment, and trains disruption duration are known, the objective is to establish a new timetable that brings impact in terms of optimizing the objective functions values while adhering to given constraints. Model of this study includes maximizing service reliability as new objective function, and new parameters were introduced with varying number of parallel tracks availability at stations, new block-oriented headway conditions and real-time schedule modification. With two objectives, our Mixed Integer Programming model will be solved using Goal Programming (GP) method and referred to as Mixed Integer Goal Programming (MIGP) model.

Indices

i	:	Trains index	
J	:	segments index	
k	:	events index	
t	:	tracks index	
T	:	Set of trains	, $i \epsilon T$

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B : Set of segments , $j \in B$

$K_i^{f_i}$: ordered set of i train event , $k \epsilon K_i^{f_i}$

$L_j^{g_j}$: ordered set of j segment event , $k \epsilon L_j^{g_j}$

$\Re$: Set of parallel tracks on a segment j

Model parameters

d_k^S : event k pre-planned departure time

a_k^S : event k pre-planned arrival time

Δ_k : constant minimum running time of event k

l_j : type of segment j; $l_j = \begin{cases} 1, & \text{if segment } j \text{ is a station segment} \\ 0, & \text{otherwise} \end{cases}$

p_i : train i priority; $p_i = \begin{cases} 1, & \text{if } i \text{ is a normal train} \\ 0, & \text{if } i \text{ is a high priority train} \end{cases}$

δ_j : time consumed to pass a non station segment j

η_j : time consumed to pass a station segment j

α : minimum safe distance between two consecutive trains

M : large positive constant

Model decision variables

d_k^N : event k newly rescheduled departure time

a_k^N : event k newly rescheduled arrival time

z_i : train i delay time

r_k^t : event k occupancy of track t

$$r_k^t = \begin{cases} 1, & \text{if event } k \text{ utilize track } t, k \epsilon K_i^{f_i}, k \epsilon L_j^{g_j},\ t \in \Re, j \in B \\ 0, & \text{otherwise} \end{cases}$$

$G_{k\hat{k}}$: the dispatch decision for event k and the next event $\hat{k}$

$$G_{k\hat{k}} = \begin{cases} 1, & \text{if event } k \text{ precedes event } \hat{k}, \hat{k} \in E, k < \hat{k} \\ 0, & \text{otherwise} \end{cases}$$

τ_i : Pre-fixed time for train i to arrive at the final destination

$$\tau_i = \begin{cases} 1, & \text{if train } i \text{ arrives with delay exceeding } w \text{ time unit}, i \in T \\ 0, & \text{otherwise} \end{cases}$$

Objective functions

$$\text{Minimise} \quad Z = \frac{\sum_{i=1}^{u} z_i}{\sum_{i=1} \tau_i} \tag{1}$$

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$$\text{Maximize} \quad R = \frac{}{n} \tag{2}$$

subject to:

$$a_k^N \leq d_{k+1}^N, \quad k \in K_i^{f_i}, \quad i \in T, \quad p_i = 1 \tag{3}$$

$$a_k^N \geq d_k^N + \Delta_k, \quad k \in K_i^{f_i}, \quad i \in T, \quad p_i = 1 \tag{4}$$

$$a_k \geq d_k, \quad k \in K_i^{f_i}, \; i \in T, \; k = \psi, \; p_i = 1 \tag{5}$$

$$a_k^N - d_{k+1}^N = 0, \quad k \in K_i^{f_i}, \quad i \in T, \quad p_i = 0 \tag{6}$$

$$a_k^N - d_k^N = \Delta_k, \quad k \in K_i^{f_i}, \quad i \in T, \quad p_i = 0 \tag{7}$$

$$d_k^N - d_k^S \geq 0, \quad k \in K_i^{f_i}, \quad i \in T \tag{8}$$

$$d_k^N - d_k^S = 0, \quad k \in K_i^{f_i}, \quad i \in T, \quad d_k^S > 0 \tag{9}$$

$$a_k^N - a_k^S = 0, \quad k \in K_i^{f_i}, \quad i \in T, \quad a_k^S > 0 \tag{10}$$

$$a_k^N - a_k^S \leq z_k, \quad k \in K_i^{f_i}, \quad i \in T \tag{11}$$

$$\sum_{t=1}^{\Re_j} r_k^t = 1, \quad t \in \Re_j, \; k \in L_j^{g_j}, \quad j \in B \tag{12}$$

$$r_k^t + r_{\hat{k}}^t - 1 \leq G_{k\hat{k}} + G_{\hat{k}k}, \quad t \in \Re_j, \; k, \hat{k} \in L_j^{g_j}, \; j \in B, \; k < \hat{k} \tag{13}$$

$$G_{k\hat{k}} + G_{\hat{k}k} \leq 1, \quad k, \hat{k} \in L_j^{g_j}, \; j \in B, \; k < \hat{k} \tag{14}$$

$$(\alpha\delta_j + M)G_{k\hat{k}} - d_{\hat{k}}^R + a_k^R \leq M, \quad k, \hat{k} \in L_j^{g_j}, \; j \in B, \; k < \hat{k}, \; l_j = 1 \tag{15}$$

$$(\alpha\eta_j + M)G_{k\hat{k}} - d_{\hat{k}}^R + a_k^R \leq M, \quad k, \hat{k} \in L_j^{g_j}, \; j \in B, \; k < \hat{k}, \; l_j = 0 \tag{16}$$

$$(\alpha\delta_j + M)G_{k\hat{k}} - d_k^R + a_{\hat{k}}^R \leq M, \quad k, \hat{k} \in L_j^{g_j}, \; j \in B, \; \hat{k} < k, \; l_j = 1 \tag{17}$$

$$(\alpha\eta_j + M)G_{k\hat{k}} - d_k^R + a_{\hat{k}}^R \leq M, \quad k, \hat{k} \in L_j^{g_j}, \; j \in B, \; \hat{k} < k, \; l_j = 0 \tag{18}$$

$$z_i - w \leq M\tau_i \quad i \in T \tag{19}$$

$$d_k^N, a_k^N, z_i \geq 0, \quad i \in T, \; k \in E, \tag{20}$$

$$r_k^t \in \{0,1\} \quad k \in L_j^{g_j}, t \in \Re_j, j \in B \tag{21}$$

$$G_{k\hat{k}}, G_{\hat{k}k} \in \{0,1\}, \quad k, \hat{k} \in E, \; k < \hat{k} \tag{22}$$

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$$\tau_i \in \{0,1\}, \qquad i \in T \tag{23}$$

Description of model

Objective function (1) is to minimize the sum of trains delay time. Objective function (2) is to maximize trains service reliability. Constraint (3) indicates that a train event can only begin after its predecessor train event is finished. Constraint (4) dictates the minimum running time for each train event k in which a normal train must finish its running time Δ_k to end the train event. Constraint (5) states that events must immediately resume once the service is recovered after disruption. Constraint (6) is to ensure sequence of train events according to the original schedule is followed. Constraint (7) states that trains should adhere to departue and arrival time as in the planned schedule once satisfying at least Δ_k running time. Constraint (8) controls the rescheduled departure time such that it is not earlier than the originally scheduled departure time. The earliest departure time must at least equal to the original departure time of that event at station. Constraints (9) and (10) guarantee that events which have been completed before disruption follow the original timetable. Constraint (11) describes that total delay of train is the difference between rescheduled and original arrival times. Constraint (12) ensures only one train use a track at any time. To satisfy number of parallel tracks at different segment, Constraint (13) specify that concurrent events at a segment must not be greaer than the track capacity. Constraint (14) control the sequence of event k and $\hat{k}$ to ensure that either one of the binary variables $G_{k\hat{k}}$ or $G_{\hat{k}k}$ take a value '1'. Constraints (15) until Constraints (18) states the conditions for minimum headway between two consecutive trains occupying the same track. If event k is predecessor to event $\hat{k}$, then Constraint (15) and Constraint (16) are active. Otherwise, Constraint (17) and Constraint (18) applied. Constraint (19) determines if service delay exceed the time window. Constraint (20) until Constraint (23) specify the decision variables.

Few assumptions were applied. During model testing, models are executed based on pre-specified disruption time and duration. Linear route is assumed and all trains must visit all designated stations. All affected trains trains are dispatched according to original route and no segment is taken out. No cancelation is allowed. Total delay time during weekdays is not different from that during weekends. Tracks are bi-directional thus up direction line can be utlized for down direction line, if needed. Each train suits any track and a train is at most a six-car train. Location and speed of all trains are known. Dwell time of trains at stations is included in event running time. Trains follow the speed limit of track segment. High-priority fast train is fixed to run as indicated by the timetable as long as at least one track is available.

Solution Algorithm: Headway and Order Scheme *(HOS)*

HOS heuristic is applied to ensure solution is produced within reasonable computing time and to lessen computational complexity by prioritizing trains and their orders and solving the whole model. The MIGP model is relaxed by fixing the value of $\boldsymbol{G_{k\hat{k}}}$ and $\boldsymbol{G_{\hat{k}k}}$ so model has fewer constraints and process of finding the solution is accelerated, enabling approximate solutions to be obtained faster. The novel HOS has been tested based on small size data (Shuib & Alwadood, 2017) followed by model refinement. Refinements for constraints made prior to full scale computational experiment are as follows: i) involve disruptions at station segments only; ii) block-oriented headway is established which uses 4 minutes minimum headway time for station segments and 3 minutes for non-station segments; iii) for experiment, cases comprises of situations with ETS ahead of disruption location, or otherwise; iv) when priority is to ETS, next priority is either recovered train or normal scheduled train (NST). As a result, there are 2016 constraints, 124 events and 1145 decision variables for MIGP model that targets to provide rescheduling solutions promptly after disruption. These rules are applied: i) existence of ETS ahead that is due to pass the very same segment – priority wil always be prime train. The second

ISSN: 2622-5778 (online)
Advances in Transportation and Logistics Research
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priority will be any events nearby of same direction which resume their journey after allowing ETS to pass first; ii) prioritize NST - NST train event is considered as higher priority against prime train event and thus, the latter has to wait until there is a safe distance between them; and iii) when there is no ETS ahead - events are scheduled according to order in original schedule. The structure of HOS is given in Figure 2.

Discussion and Result

The MIGP model is solved using preemptive GP approach based on first goal (to minimize total delay time), followed by imposing additional constraint based on first goal's solution. The modified MIGP model is then solved based on second goal, to maximize service reliability. Table 2 presents comparison of solutions obtained when priority is either the prime train or NST, with and without ETS ahead. As experiments were done by setting disruption duration as 5, 6, 7 … up to 15 minutes, results were consolidated by taking average of results. When prime train is given the priority, average delay time recorded for both, with and without ETS, are smaller than those results if NST is given top priority. In addition, giving priority to prime train generates higher quality solution (in terms of delay time and reliability). KTMB is recommended to grant higher priority to prime train after recovery from disruption provided that disruption duration does not exceed 15 minutes. Without ETS ahead, computation time is recorded as 36 seconds.

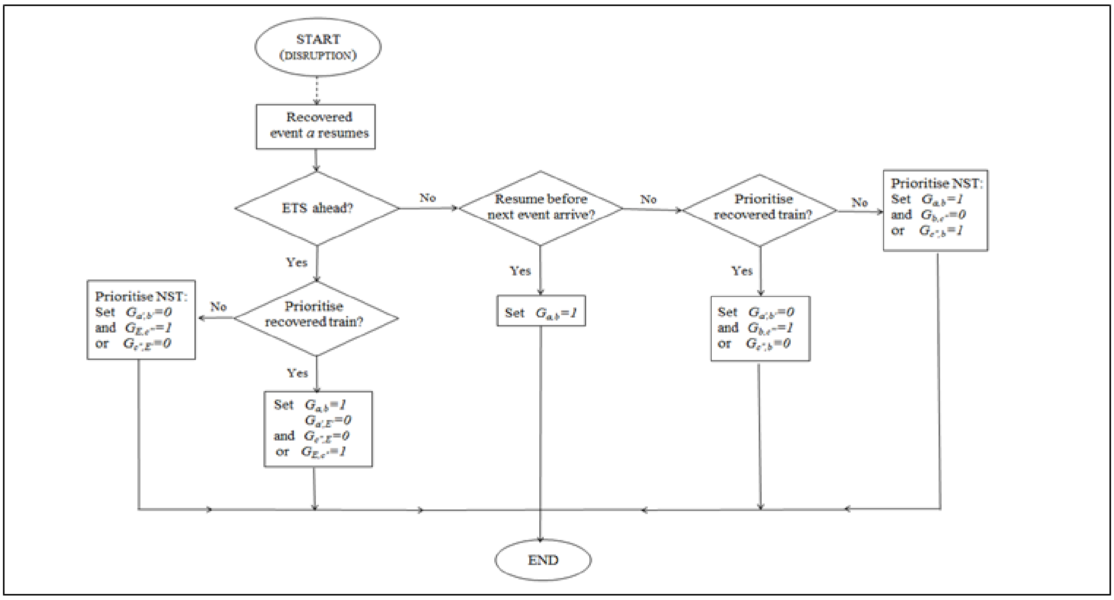

Figure 2: The Structure of Headway and Order Scheme (HOS)

Table 2: Comparison of Results for Different Trains Priority with or without the Presence or Absence of ETS

HOS Priority	Total Delay Time and Reliability	with ETS	No ETS
Prime train	Average TDT *(min)*	21.1	13.4
	Average SR (%)	84.9	83.9
NST	Average TDT *(min)*	25.5	26.0
	SR (%)	72.3	66.7

Note: Total delay time (TDT); service reliability (SR)

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Table 3: Results Generated for Selected Duration of Disruption with and without ETS Ahead

	Disruption durations		
with ETS Ahead	5 minutes	10 minutes	15 minutes
Average TDT *(minutes)*	20	20	26
Average SR (%)	88.9	88.9	72.3
with No ETS Ahead	5 minutes	10 minutes	15 minutes
Average TDT *(minutes)*	20	20	26
Average SR (%)	88.9	88.9	72.3

Table 3 display results when MIGP model with HOS was executed with strict disruption durations of 5, 10 and 15 minutes. Average total delay time is consistent at 20 minutes with average service reliability of 88.9% if durations are 5 or 10 minutes. Results deteriorated if duration is 15 minutes.

Conclusion

The MIGP with HOS has yield remarkable and practical results and could be used as a foundation for new decision support system that providess quick solution and minimizes train delays and maximizes service reliability. The MIGP model can be extended for rescheduling other types trains such as KTM Intercity, LRT and Monorel. Future research could improve the MIGP model and HOS to see their performance when tested using larger data set. Model formulation can involve connecting trains with different priority level.

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