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OPTIMUM RESCHEDULING OF TRAIN PLATFORMING AND ROUTING PLANS AT PASSENGER STATIONS DURING A DISRUPTION

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ABSTRACT
The susceptibility of railway operations to disruptions and its over-dependence on compliance to a schedule necessitates contingency measures to be put in place to manage such disruptions. The efficiency of a railway system has a lot to do with how robust such measures are. These disruptions are uncertain and as such, provided measures to counter them do not always agree with reality. The problem becomes more complicated when it occurs in real-time and at the station. To solve such problem, a complete resolution of all conflicting activities (train operations and maintenance tasks) must be carried out. These mutually exclusive activities compete for track allocation in the railway network. Existing solutions mainly focus on solving conflicts in train operations and neglect existing maintenance tasks. This research presents a MILP formulation of the problem and demonstrates how a disturbed train operations plan can be rescheduled while considering station infrastructure maintenance tasks. Four practical scenarios of this problem are presented and analyzed. Test results from real-life data demonstrate the efficacy of this formulation in handling various practical scenarios of the described problem within reasonable computational times.

Keywords: Operations research, Train rescheduling, Infrastructure maintenance, Mixed integer linear programming, Disruption management

INTRODUCTION
Railway infrastructure consists of a network of rail tracks along which trains move. A stage in railway infrastructure access planning involves the strategic design of train timetable with defined infrastructure maintenance timeslots across the railway network (Lu et al., 2022). The development of robust train timetables is still an active research area due to the intricacies and uncertainties surrounding railway operations (Zhang et al., 2020). Of such intricacies is coming up with a schedule that coordinates train operations and rail infrastructure maintenance. Maintaining the rail infrastructure is paramount since it enables the safe movement of trains along rail tracks. These mutually exclusive activities are in competition of timeslots on the space-time graph of a railway network D'Ariano et al., 2019).

The most widely used strategy for preventing infrastructure failure in railway industries around the world is through well-structured maintenance plans (Lidén, 2015). These maintenance plans allocate track sections (track possession) to maintenance crew for preventive maintenance tasks (in the form of physical inspections) (Luan et al., 2017) and renewals of degraded (or aged) rail track components (e.g. signals, ballast, sleepers etcetera) (Zhao et al., 2006). Through these inspections, identified major potential failures (that could not be remedied during the routine inspections) are scheduled for execution in a later time period (He, 2014).

Although, the structural and operational integrity of rail infrastructure is being ensured through preventive maintenance tasks (PMTs) and scheduled renewals of infrastructure components, failure of infrastructure components often occurs which necessitates impromptu corrective maintenance tasks (CMTs) to be scheduled (Albrecht et al., 2013). When this failure is critical (in time) that train movements along the affected part of the rail infrastructure have to be stopped immediately, it translates to cancelling, queuing and/or rerouting trains (Zhan et al., 2022). Apart from the delay this may cause to affected trains, it also means that the affected portion of the railway network (scheduled for impromptu maintenance) has to be removed from all candidate routes when rerouting trains. This task becomes more difficult at complex stations where the station routing and train platforming problems have to be resolved in real-time (Hong et al., 2021). In this paper, these two problems are referred to as train routing and scheduling (TRS) problem.

The problem described above is not new in the literature, as several researchers have proposed its solution (Chakroborty & Vikram, 2008; Liden, 2015). However, one thing these proposals have in common is neglecting scheduled preventive maintenance tasks at the station when solving the problem. This will obviously create conflicting assignments in rail networks that use preventive maintenance as the strategy of maintaining the working condition of its infrastructure. Thus, the contribution of this paper.

METHODOLOGY
Model Formulation
Input parameters and decision variables
Input parameters to the model are sourced from train platforming plan, station layout, preventive maintenance tasks schedule, and corrective maintenance tasks to be scheduled. The following input parameters are thus defined.

V = Set of nodes.
E = Set of edges.
H = Set of approach directions
G = Set of departure directions
I_h = Set of trains that will arrive at the station within [t_1, t_2] where t_1 and t_2 are the lower and upper bound of the rescheduling time horizon respectively.
T = size of set I_h.
a_i = Arrival time of train $i \in I_h$ to station home signal

w_i = Maximum allowable waiting time of train $i \in I_h$ at station home signal
h_t = Minimum headway time between trains.
I_p = Set of trains occupying platforms at t_1 (due to previous assignment).
I = Set of trains that would have visited the station within [t_1, t_2]. i.e. $I = I_h \cup I_p$.
r^k = Release time associated with platform k.
A = Set of all platforms in the station.
P = size of set A.
B = Set of platforms occupied by trains in set I_P. i.e., $B \subset A$.
d_i^k = Dwell time of train $i \in I$ at platform $k \in A$.
R^I = Set of inbound routes.
R^o = Set of outbound routes.
M_c = Set of CMTs to be scheduled.
M_p = Set of PMTs.
T_z = Time required to carry out maintenance task $z \in M_c \cup M_p$.
S_z = Start time of maintenance task $z \in M_c \cup M_p$. This time is equal to t_1 for all corrective maintenance tasks.
E_z = Set of edges which define the position of maintenance $z \in M_c \cup M_p$.
R_z = Set of train routes affected by maintenance task $z \in M_c \cup M_p$.i.e. $R_z = (route \backslash (u,v)_{route} \in (R^I \cup R^O) \cap E_z)$
The decision variables are:

$$X_i^r = \begin{cases} 1 \text{ if train i is assigned to route } r \\ 0, otherwise \end{cases}$$

$$\alpha_{ij}^k = \begin{cases} 1 \text{ if trains i and j are assigned to the same platform k} \\ 0, otherwise \end{cases}$$

$$\beta_i^k = \begin{cases} 1 \text{ if train i is assigned to platform k} \\ 0, otherwise \end{cases}$$

$$\gamma_{ij} = \begin{cases} 1 \text{ if train i leaves the home signal before train j} \\ 0, otherwise \end{cases}$$

$$\eta_{ij} = \begin{cases} 1 \text{ if train i and j share atleast an edge } (u,v) \text{along their routes} \\ 0, otherwise \end{cases}$$

$d_i = Departure\ time\ of\ train\ i \in I_h\ from$ home signal.

Constraints definition

Apart from the safety and operational constraints common to all versions of the TRS problem, certain business constraints and threshold values exist, which vary from one railway industry to another.

Train schedules and routing

Each arriving train $i \in I_h$ is assigned an arrival route $r \in R^I$, a platform $k \in A$, and a departure route $r \in R^o$. Train *i*, based on its approach direction has *'n'* candidate routes it can take to a potential platform. Similarly, based on its departure direction, *i* has *'m'* candidate routes it can choose from that connect its assigned platform to its departure direction. Hence, route selection variables X_i^r are used to define which arrival and departure routes are assigned to train *i*. Train *i* can choose only one arrival route and only one departure route. Hence,

$$\sum X_i^r = 1 \ \ \forall i \in I \ \ \forall r \in R^O \qquad (1)$$

$$\sum X_i^r = 1 \ \ \forall i \in I_h \ \ \forall r \in R^I \qquad (2)$$

Conflicts

Platform occupation in previous assignment

A train can only be assigned to one platform.

$$\sum_{k=1}^{P} \beta_i^k = 1 \ \ \forall i \in I_h, \forall k \in A \qquad (3)$$

However, because this is rescheduling in real-time, it is likely some platforms are already occupied at the beginning of the rescheduling time horizon (t_1) by trains in I_p. Hence, all platforms are associated with a release time (r^k), which is the time at which previous platform occupation assignments will elapse for each platform. For platforms currently unoccupied at t_1, $r^k = t_1$. To ensure that a train is not assigned a platform already occupied by another train (in set I_p) departure of train *i* from the home signal will also have to satisfy,

$$d_i \geq r^k \beta_i^k \quad \forall i \in I_h, \forall k \in B \qquad (4)$$

Conflict between train operations and maintenance tasks

Each maintenance task *z* is modelled (in terms of position) by a set of edges (u_z, v_z). All CM tasks are assumed to start at the same time (t_1) and end at their respective durations (T_z). Set R_z contains all routes having at least an edge in E_z. These routes will be unavailable (to allocate to trains) for the duration of the maintenance task *z* if *z* is a CMT. This applies to scheduling CMTs along station tracks in the interlocking area. However, for CMT along a platform track, extending the release time of the affected platform (to the duration of the CMT) suffices scheduling the CMT. Since trains can only use routes in R_z after the maintenance period,

$$d_i \leq a_i + w_i + T_z^{(u,v)} X_i^r$$
$$\forall i \in I_h, \forall (u,v) \in r, r \in R_z \cap R^I, z \in M_C \qquad (5)$$

For routes not in R_z, T_z is set to zero and w_i is the maximum waiting time (at home signal) allowed for train *i*. Similarly, a train cannot choose a route in R_z before the end of maintenance task on its way out of the station.

$$d_i + h_t + d_i^k \geq T_z^{(u,v)} X_i^r$$
$$\forall i \in I_h, \forall k \in A, \forall (u,v) \in r, r \in R_z \cap R^I, z \in M_C \qquad (6)$$

While conflict between train operations and PMTs is allowed, this conflict is minimized in the objective function. Most times, several maintenance tasks can be carried out along a rail track section at the same time. As such, all maintenance tasks are assumed to be non-conflicting with one another.

Conflict between train pairs

Similar to Sels et al. (2014) and Chakroborty and Vikram (2008), conflict is modelled to exist between train pairs and a conflict filter is introduced using the following three sets:
Set X contains train pairs *(i, j)* whose arrival times at home signal are so far removed that we are guaranteed of a conflict-free movement between them.

$$X = \{(i,j) \mid a_{i,h} \geq a_{j,g} + w_i + d_i^k + h_t\}$$
$$\forall i \in I_h, \forall j \in I_h, \forall h \in H, \forall g \in H, \forall k \in A, i \neq j \qquad (7)$$

Set Y contains train pairs *(i, j)* such that train *j* arrives at the station before train *i* leaves the station. Although train *i* has departed the home signal, we still need to ensure that a safety headway is maintained between these pairs when they share a common rail resource.

$$Y = \{(i,j) \mid a_{i,h} + w_i < a_{j,g} < a_{i,h} + w_i + d_i^k + h_t\}$$
$$\forall i \in I_h, \forall j \in I_h, \forall h \in H, \forall g \in H, \forall k \in A, i \neq j \qquad (8)$$

Set Z contains train pairs *(i, j)* whose arrival times at station home signal are so close that either of them can depart first.

$$Z = \{(i,j) \mid a_{j,g} \leq a_{i,h} + w_i \ and \ a_{i,h} \leq a_{j,g} + w_j\}$$
$$\forall i \in I_h, \forall j \in I_h, \forall h \in H, \forall g \in H, i \neq j \qquad (9)$$

The decision variable γ_{ij} can be 0 or 1 for train pairs in set Z, unlike in sets X and Y (where it is always equal to 1). Hence, it is necessary to constrain γ_{ij} to 1 if train *i* arrives at the home signal before train *j* and both trains are on the same arrival track (at the same home signal). To achieve this, a set V (subset of Z) contain all train pairs whose entry track is the same.

$$V = \{(i,j) \mid a_{i,h} \leq a_{j,g} \text{ and } g = h\}$$
$$\forall i \in I_h, \forall j \in I_h, \forall h \in H, \forall g \in H, i \neq j \qquad (10)$$

The constraint for γ_{ij} can be written as:

$$\gamma_{ij} = 1 \quad \forall (i,j) \in X \cup Y \cup V \qquad (11)$$

In line with the assumption of a sectional release route locking method adopted, safety headway should be maintained when trains share at least an edge in their route. Hence, departure from the home signal should satisfy:

$$d_j \geq d_i + h_t + d_i^k \alpha_{ij}^k + M(\eta_{ij} + \gamma_{ij} - 2)$$
$$\forall (i,j) \in Y \cup Z, \forall k \in A, \forall (u,v) \in r_i \cap r_j, i \neq j \qquad (12)$$

Objective function

To maintain some level of adherence to the original schedule, the objective function will aim to minimize the deviation of the rescheduling process. The first component deals with deviation from departure time at home signal. Since the original plan does not allow any delay at station home signal, there is need to minimize the consequential delay of trains at station home signal while rescheduling. Also, different trains carry different operational value and for this reason, a cost, associated with the delay of train *i* at station home signal (c_i) is introduced.

The total cost of delaying trains at home signal can be expressed as:

$$\sum_{i=1}^{T} c_i(d_i - a_i) \quad \forall i \in I_h$$

The second component minimizes deviation in platform allocation. The advantage of minimizing this deviation is twofold. First, passengers will not be burdened with moving to a different platform after the reassignment. This will create discomfort if the reassigned platform is not the same as the platform communicated to passengers earlier. To achieve this, a matrix of costs (inconvenience cost) associated with reassigning a train *i* from platform track *k* to a different platform track *l* (c_i^{kl}) is generated based on the station layout. This cost is based on the relative distance (ease of transfer) between platform tracks *k* and *l* and translates to time and inconvenience costs on passengers moving from platform track *k* to platform track *l*. This cost is zero if platform tracks *l* and *k* share the same platform.

Second, in rescheduling passenger train timetables, it is important to restore the plans to the original (announced) schedules as soon as possible with little (or no deviation) from the announced schedule. A change in platform allocation, especially to trains whose departure times from platform will be beyond the upper bound of the rescheduling horizon (these trains will be in set I_p in the next rescheduling horizon and if the platform allocated to them is not the same as the original assignment, restoration to original plan might not be achieved at the current rescheduling phase). To this effect, we add additional cost (restoration cost, c_i^k) to reassigning such trains to a different platform. This cost is zero for trains whose departure time from platform is within the rescheduling time horizon.

The total sum of these costs can be expressed as:

$$\sum_{i=1}^{T} \sum_{k=1}^{P} (c_i^k + c_i^{kl}) \beta_i^k \qquad \forall i \in I_h, \forall k \in A, \forall l \in A$$

The third and fourth components minimize assignment of trains to rail tracks scheduled for PM tasks. To achieve this, sets of trains whose use of rail track coincide with a PM task on those tracks (I_z) are defined. Penalty is incurred on assigning these trains to such rail tracks within the planned duration of the preventive maintenance tasks. The sums of these costs can be expressed as:

$$\sum_{i=1}^{T} c_i^z X_i^r \quad \forall i \in I \cap I_z, \forall r \in R^I \cup R^O$$ and

$$\sum_{i=1}^{T} c_i^z \beta_i^k \quad \forall i \in I \cap I_z, \forall k \in A$$

Where $I_z = \{i \mid S_z + T_z \geq d_i,\ d_i + d_i^k \geq S_z\}$

$$\forall i \in I_h, \qquad \forall k \in A, \forall z \in M_p$$

The complete formulation of the train operations and maintenance scheduling (TOMS) model is given below.

$$\min\ W_1 \sum_{i=1}^{T} c_i(d_i - a_i) + W_2 \sum_{i=1}^{T} \sum_{k=1}^{P} (c_i^k + c_i^{kl}) \beta_i^k + W_3 (\sum_{i=1}^{T} c_i^z X_i^r + \sum_{i=1}^{T} c_i^z \beta_i^k)$$

subject to:

Equations (1) - (12)

Computational Experiments

The algorithm is implemented in python and the resulting MILP model is solved using DOCPLEX python package (version 2.11.176). All experiments are carried out on an intel CORE i5 1.80 GHz processor with 8 Gb RAM.

On a scheduled train timetable at Zhengzhou railway station (in east-central part of China), random perturbations drawn from Weibull distribution were introduced on arrival times of trains at station home signal to simulate late arrival delays. Late arrival delays agree well with Weibull distribution (Yuan, 2006; Otu et al., 2022). These data together with the python model implementation are available at https://github.com/AliyuMani/ModelTM.

The effectiveness of our model formulation to handle delay management and schedule corrective maintenance tasks is assessed using these delay instances on two extreme rail track demand conditions:

a. Peak demand of rail tracks for scheduling preventive maintenance tasks.
b. Peak demand of rail tracks for scheduling train operations.

A total of hundred (fifty each of the peak demand periods) delay instances were generated. In China, general-speed-railway (GSR) network unlike the high-speed-railway (HSR) network, does not have an exclusive train-free timeslot for infrastructure maintenance. As such, trains (though with lesser traffic density) move across the GSR network even at night. However, most of the preventive maintenance tasks are scheduled to take place at night. Thus, the first peak demand will most likely be during nighttime while the second is usually during daytime when there is peak demand for train services.

To each of the cases of rail track demand conditions, random CMTs (whose duration and nature are drawn from consultations with dispatchers and maintenance planners from Zhengzhou railway enterprise) were introduced. Depending on the location and nature of such CMTs, they can be described as either:

A. CMTs that render some portion of station interlocking area inaccessible or,
B. CMTs that render platform(s) inaccessible.

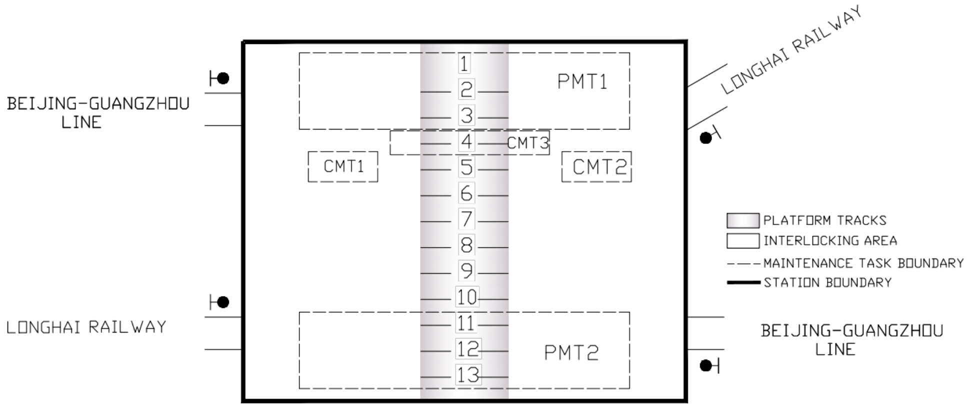

Figure 1: Position of infrastructure maintenance tasks scheduled (PMT) and to be scheduled (CMT).

Figure 1 shows the relative positions of the maintenance tasks used in these experiments. The delay values (Table 2) are the averages of all random instances used in each of the test scenarios. The CMTs are of varying duration (with the same start time) and all PMTs are for a duration of at least one hour with different start time (Table 1).

Table 1: Duration of Infrastructure maintenance tasks

Maintenance task	Duration (min)
PMT1	60
PMT2	45
CMT1	60
CMT2	60
CMT3	45

Scenario 1

This scenario is derived from situations where there is peak demand of rail tracks to schedule preventive maintenance tasks and at the same time, infrastructure condition necessitates scheduling corrective maintenance tasks along interlocking area (A) or platform tracks (B). Simulated late arrival delays further disturbs the system and creates more conflicts.

Table 3 shows how these conflicts were resolved. All arriving trains are successfully platformed and no PMT is cancelled. Although table 3 could lead one to conclude that CMT position has no influence on the degree of disturbance (during rescheduling process), further experiments conducted by randomly changing CMT position revealed that the position of CMT indeed has a remarkable influence on degree of disturbance (Table 4). This agrees with the fact that, the practical feasibility of a train timetable at a station is not only dictated by the train platforming capacity but also the capacity of the station throat.

Scenario 2

This scenario is derived from situations of peak demand of rail track to schedule train operations. This usually occurs during rush hours when demand for train services is at peak. At the same time, infrastructure condition necessitates scheduling corrective maintenance tasks along interlocking area (A) or platform tracks (B). Schedules during rush hour are usually characterized by little tolerances for delays. As such, introducing any activity that requires track ownership during this period will significantly disrupt the system.

Table 2: Traffic and infrastructure conditions in test scenarios

Test Scenario	No. of trains	Max. delay (s)	Ave. delay (s)	PMTs	CMTs
1A	26	420	130	PMT1, PMT2	CMT1, CMT2
1B	26	420	130	PMT1, PMT2	CMT3
2A	38	420	134	N/A	CMT1, CMT2
2B	38	420	134	N/A	CMT3

Table 3: Optimization results with late arrival time delays

Test scenario	Trains delayed* (#)	PMTs Cancelled (#)	Platform Change (#)	Solve time (s)	Run time (s)
1A	0	0	2	9.2	19.1
1B	0	0	2	8.8	17.5
2A	0	N/A	1	15.5	46.4
2B	0	N/A	1	19.8	58.1

*Number of trains delayed at station home signal

Rescheduling passenger trains should favor a plan that resolves ensuing conflicts with little additional disturbance to the system. One factor crucial to achieving this plan is the length of the rescheduling horizon. The rescheduling horizon of two hours (in test instances) was arbitrarily chosen with the consideration that recovery time (60 minutes for results in

Table 3) should be provided after all scheduled CMTs have been completed to allow return to the original plan. This recovery time should be the minimum time for which the disturbed system will optimally recover to the original plan.

Table 4. Influence of CMT position on optimization results (for scenarios 1A and 1B)

	Trains delayed at home signal	PMTs Rescheduled	Platform change	Solve time	Run time
% diff. with respect to CMT position	0.0	12.5	30.0	5.6	6.2

Restoration to original plan of interest in this experiment is minimizing late departure of trains from the station and ensuring that trains with departure time beyond t_2 are allocated their original platforms. Delay of train at home signal will lead to a departure delay from the station (since dwell time of trains is fixed). Such late departures will cause a rippled secondary delay that will propagate to other stations across the network. A different platform allocation to trains (those leaving the station after t_2) on the other hand will most likely extend the disruption outside the current rescheduling horizon.

This restoration is ensured by a recovery time and a restoration cost (c_i^k, in the objective function). When the recovery time is too short, the system will be too disturbed, causing inconveniences to stakeholders, or perhaps yielding infeasible results. A long recovery time will considerably increase the size of the problem, invariably increasing computational time (Figure 2). Besides, an extended upper limit of the rescheduling horizon will mean information about actual arrival time of some late trains will not be accurately captured since they are too far in time from arriving at the station.

Deciding the optimum length of recovery time is a compromise between number of affected trains and degree of disturbance one is willing to accept. Table 5 shows the minimum recovery time for which all late arriving trains are reallocated their original platforms with no train delayed at home signal.

Table 5: Minimum recovery time required time to return to original plan.

Scenario	Recovery time (min)	PMTs cancelled (#)	Platform change (#)	Solve time (s)	Run time (s)
1A	0	0	2	4.3	16.8
1B	15	0	3	9.7	28.7
2A	5	N/A	3	11.0	45.9
2B	20	N/A	4	14.3	52.8

The compromise in this experiment is that as much as possible number of trains could be affected (in terms of platform change mostly) if no train is delayed at home signal and preferably no PMT is cancelled. It is worthy of note that, extending the recovery time will although affect more trains (with tolerable delays at home signal) but lessen the degree of disturbance in platform allocations. This can be seen when optimization results in Tables 3 (with recovery time of 60 minutes) and 5 are compared.

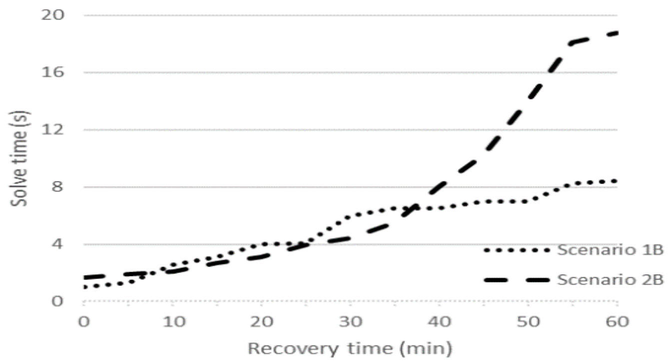

Figure 2: Influence of recovery time on solve time

Another factor that determines the degree of disruption is the duration of CMTs. Since CMT duration is tied to the upper bound of the rescheduling horizon (t_2), a longer CMT duration will extend the rescheduling horizon (hence increased problem size) and likely take up assigned resources. This will undoubtedly create more conflicts. Table 6 shows the influence of CMT duration on the degree of disruption. Values in Table 6 are for a constant rescheduling horizon.

Table 6: Optimization results for different durations of CMT (assuming all CMTs in Figure 1 have equal duration)

CMT duration (min)	Recovery Time (min)	Scenario	PMT Cancelled (#)	Platform Change (#)	Solve Time (s)	Run Time (s)
30	90	1B	0	1	3.8	16.9

		2B	N/A	0	15.1	36.4
60	60	1B	0	2	3.8	17.1
		2B	N/A	0	14.8	33.9
90	30	1B	0	2	3.8	18.3
		2B	N/A	4	15.0	35.8
120	0	1B	0	2	3.9	19.6
		2B	N/A	5	15.5	42.9

CONCLUSIONS AND FURTHER RESEARCH

In this research, a mathematical model of TRS problem has been formulated with mesoscopic level of infrastructure detail. Two effects of railway disturbance were modelled. The first being trains late arrival delay at stations and the second, trains' inaccessibility to some portion of station track due to an impromptu CMT. The effectiveness of the model has been demonstrated in resolving the modelled effects in real time on real life data. Mesoscopic modelling of station infrastructure allows the optimum exploitation of rail resources in conflict detection and resolution. This is especially important when track possessions are to be accurately captured in resolving conflict.

Optimization results showed both station routing problem and train platforming problem having similar sensitivity to changes in parameters. For the same train traffic and infrastructure condition, scheduling CMT at interlocking area (which considerably alters a station routing plan) or at platform tracks (which considerably alters a train platforming plan) has similar effects on trains and PMTs schedules. Hence, with track-occupation-time as a variable, we can say that, the train platforming problem is an extended version of the station routing problem.

In a model that minimizes four goals at the same time, the bottleneck is in deciding how to optimally come up with the weight of each goal that satisfies all stakeholders involved. A version of the formulation that combines these goals into one will be an interesting research topic. In future research, we intend to look for a better way to resolve this impasse.

Rescheduling PMTs within a short rescheduling horizon is somewhat infeasible. However, a formulation that only cancels the PMTs after a trial rescheduling (within the rescheduling horizon) will be a better option. This comes at a cost since an extended rescheduling period will increase the size of the problem and solve time and may not guarantee a feasible solution within reasonable computational time. One way to solve this problem is by compartmentalizing the initial PMTs in position. These smaller tasks (in position) can then be scheduled while minimizing the time required to move equipment and personnel from one location to another.

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