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Value of rail inspection reschedules

Mohd Haniff Osman[1,2] and Sakdirat Kaewunruen[1]

Abstract

A regular rail inspection schedule has been proposed to minimise any detrimental financial cost incurred due to operations under harsh environments. Missed opportunities to detect a defective rail could lead ultimately to it breaking, which would magnify the repair (as well as maintenance) cost, by approximately 30-35% per rail-mile. However, the performance of a pre-planned inspection schedule may be affected by disruptions in one or more element(s) of inspection such as machine/vehicle breakdown or track unavailability, which are usually unpredictable events. As part of the justification for the need to manage a disrupted inspection schedule, this paper proposes a methodology that highlights the value of rescheduling. An extensive literature search was undertaken on the rescheduling framework in order to determine appropriate policies, strategies and methods for rail inspection. As a result, the value of rescheduling is formulated as the ratio of rescheduling cost to a change in value of risk from a missed opportunity to repair a defective rail i.e., late defect detection. This numerical formula demonstrates how the proposed methodology is useful for filtering out a rescheduling strategy that has (negative) value when dealing with a disrupted rail inspection schedule. The discussion portrays several potential aspects to feasibly extend the proposed methodology on large scale of rail network.

Keywords

Rail inspection; rail maintenance; rescheduling; disruption; decision value; risk analysis; P-F interval

Introduction

Rail inspection is an important investment for every railway infrastructure manager (RIM). For example, Network Rail, a railway administrator in the UK, spent almost 9 million on inspections (excluding maintenance works) in 2011 of around 20,000km track lines[1]. According to the previous study[2], the cost exponentially grows in line with the size of the railway network and inspection requirements. Limited resources, for example, inspection vehicles and manpower, and time restrictions to assess tracks, have underpinned the need of (the predetermined) inspection schedules to effectively prioritise inspection tasks. In this regard, rail inspection is a proactive action to assure safety and operability of the tracks, However, from track capacity management viewpoint, track possession for inspections seems to be an obstacle for RIMs to offer an additional track access, especially to freight companies. It is also noted that RIMs and train companies in the European region are not eligible for inclusion under one organisation, following an endorsement of reform model in 1990[3].

A rail inspection schedule (RIS) is normally prepared several months before an operational year with respect to a RIMs objectives (e.g. safety, comfort, costs) and is subject to many technical, safety and business constraints[4;5]. In fact, a planner must wait for the disclosure of freight and passenger timetable and major possession plans as those are constraints in generating the RIS[6]. Usually, the total value of inspection decisions is known in advance due to its nature so that company resources such as equipment, inspection vehicles and manpower, are ready, and track possessions can be arranged effectively. However, due to the fact that the complexity of the RIS model increases along the amount of uncertainty associated with rail inspection and maintenance; thus, not all uncertainties are able to be taken into consideration at the design phase[7]. In line with this, performing trading model complexity with uncertainties, especially those with very low information, is necessary and it indirectly creates an opportunity for RIMSs to effectively manage disruptions.

In the meantime, disruptions are often unexpected, have a low likelihood of occurrence and their consequence is ambiguous in nature. Disruptions occur abruptly and most times, they occur beyond the control of the system owner. Landslides[8], train accidents[9] and poor contingency plans[10] are real disruptions that have occurred in the European region recently. Realising that most disruptions are unforeseeable, many studies have focused on reducing the consequences of disruptions[11] and some have employed disruption management as an underlying theory. In our previous works[12–14] the importance of adopting the theory in managing disrupted inspection schedule is discussed. Meanwhile, from a financial aspect and protecting organization's reputation rescheduling is performed in order

[1] School of Engineering, University of Birmingham, Birmingham, B15 2TT, United Kingdom
[2] Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, UKM Bangi, 43600, Malaysia

Corresponding author:
Mohd Haniff Osman, School of Engineering, College of Engineering and Physical Sciences, 52 Pritchatts Road, Edgbaston, Birmingham, B15 2TT, United Kingdom.
Tel: +44 07549 751051
Email: mxo574@bham.ac.uk

to minimise impacts from disruptions and assure the survival of the dedicated schedule until the end of targeted period i.e. a preventive maintenance cycle. For example, the effectiveness of rail maintenance decision, specifically the optimal downtime per unit time will start to decrease if there is a disruption during the day of operations[15].

As the initial inspection decisions might be altered, the value of rescheduling should be established in order to guide decision makers. The value in rescheduling is said to be created if benefits exceed total incurred costs. In such cases where value does not exist, the object of interest i.e. the rescheduling process, could demonstrate value added to rail inspection scheduling, through an introduction of innovative procedure to manage disrupted schedules. In this paper, risk and economic elements are studied in parallel to establish quantitative measures for the formulation of rescheduling disrupted rail inspection.

Mapping RIS in rescheduling framework

In complex (i.e. interrelationships between several resources exist) situations, applying changes to an initial schedule is not interesting but, in the event of disruption, changes by means of rescheduling are necessary. Fox et al. 2006[16] points out that rescheduling is a challenging operation as the minimisation of changes in the original schedule and the impact of disruptions are two principle objectives that need to be satisfied. Recently, a new study of rescheduling is highly recommended to refer to a framework designed by Vieira et al. (2004)[17] to obtain an insight about the necessary requirements to mitigate disrupted risks upon a predetermined schedule in a realistic way. Figure 1 shows four dimensions/compositions underlying the framework. Issues and development of each dimension is discussed in the following sub-sections accordingly. The scope of discussion is limited to relevant research materials associated with railways, transportation and maintenance. The focus of this study is placed on the inspection of rail component.

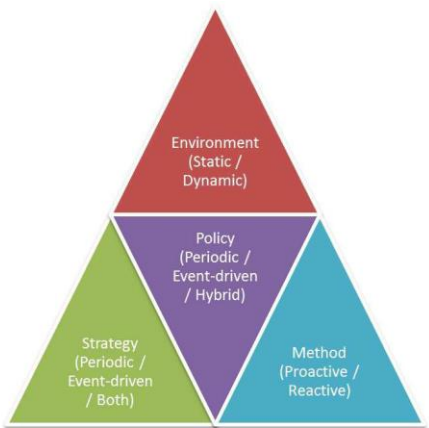

Figure 1. Interdependent components of rescheduling framework.

Dimension 1: Environment

The rescheduling environment explains which part of a disrupted schedule needs a modification. It begins by classifying the schedule into static or dynamic. In contrast to a dynamic schedule, a static schedule has a finite number of tasks. In the context of railway operation, and probably in all public transportation business, resources schedules including timetables have a finite size of tasks where their information is certain, such as the number of trips in a week, routes and fares. In fact, most railway-related schedules are decided and planned several months before the operation year starts. However, for some static schedules, even though the number of tasks is known, uncertainty in the schedule parameters might occur. For example, RIM usually know the number of tracks that need to be inspected, but, an exact inspection frequency of each track is not certain due to random failure occasions[18].

Dimension 2: Strategy

Rescheduling is a synonym to recovery action and would be performed upon disruption occurrence. In this light, disruption itself is unexpected as we do not know an exact time when it will occur even if we can study potential sources and consequences of disruption. However, those characteristics are not an obstacle to users who aim to prepare a rescheduling strategy ahead of time. Having the knowledge on what strategy needs to be implemented would ease the process of deciding whether an existing schedule requires rescheduling or not. Moreover, to what extent changes could take place in a schedule is possible in regards to the process of visualisation and estimation.

Furthermore, the preferences of schedulers/planners during the schedule design stage influences his/her approach towards disruptions. In predictive-reactive scheduling, the predetermined schedule is rescheduled in response to disruptions and other changes within the environment. In such cases, the provisional schedule could be fundamentally deviated from the original one, which may cause poor performance owing to affecting other planning activities based on the original schedule. For these reasons, some authors tend to generate a schedule that aims to act robustly in response to a specific disruption[19]. Meanwhile, Fang et al. (2015)[20] stated that establishment of a schedule that behaves in a robust way toward different disruptions is hard and becomes harder as time for rescheduling is often limited in railway systems. As stated in Cacchiani et al. (2014)[21], contingency plans are real when handling disruptions to railway timetables and are being practised in the Netherlands. There are one thousand pre-planned periodic timetables for various types of disruption. Preparation of those plans is definitely a loss in a year where no disruption occurs. Moreover, only an experienced scheduler is capable of performing a plan selection. Nevertheless, an application of predictive strategy in an uncertain environment demands extra careful observations when dealing with problem formulation, as resources, e.g. time slots, vehicles, etc., are already over-utilised.

Regardless of the chosen rescheduling strategy, the consequence level of the reschedule factor needs to be measured first. In this light, rescheduling is exempted if the consequence level is small (relative to users definition) or otherwise, the schedulers will move to the second and third steps which is finding a rescheduling solution(s) and revise the solution selection. The existence of many rescheduling methods opens an opportunity to offer several alternatives that can improve the performance of an existing schedule to the decision-makers[17]. Hence, in case the solution generates unsatisfactory results (user-defined value), the decision makers could apply the second-best alternative or they can repeat the solution step with or without the parameter changing. Consequently, there are several classification schemes introduced to reschedule methods and this study will discuss some relevant classifications the following section. As such, a rescheduling policy would help users to attain a good justification for selecting particular methods and to revise the solution.

Dimension 3: Policy

An implementation of a predictive-reactive rescheduling strategy is driven by a rescheduling policy, which refers to a type of event that orders rescheduling of an existing schedule. In a periodic situation, use of a single schedule for numbers repeatedly keeps schedulers from spending resources again on schedule generation. To own this opportunity, a scheduler should gather comprehensive information from different aspects related to the system which the schedule is operating in. For example, track inspection schedules always come after an international freight train, passenger train and major possessions schedule are announced. However, as internal and/or external environments of the system probably change due to various reasons, rescheduling the existing schedule before the next period begins could yield stability and reduce schedules performance deterioration. In this situation, a scheduler applies a periodic policy where a fresh system status focusing on irregularities is taken into account when seeking a better schedule.

As discussed earlier, a disruption might attack a schedule during its execution period. Depending on the level of consequence associated with the disruption, a range of rescheduling methods can be used to create or update a schedule. At this point, rescheduling is driven by events. In most situations, those events are not part of the schedulers consideration when creating an initial schedule due to uncertain information about them. In the case of dynamic schedules, the event is not necessarily a disruption. It could be a regular task with incomplete information. A periodic schedule also can be rescheduled due to unscheduled events. Vieira et al. (2004)[17] uses a hybrid policy term when referring to this situation.

Dimension 4: Method

Understanding which type of rescheduling strategy a user can implement when selecting a rescheduling method can be a straightforward action. For a predictive strategy, many methods ranging from evolutionary algorithms to numerical simulations have been adopted to generate a robust schedule in response to a specific disruption. Yang et al. (2014)[22] proposes a method to create predictive schedules that include inserted buffer time (idle time) as a means to absorb some level of uncertainty without rescheduling. Typically, this method employs a bottleneck algorithm to handle parameter uncertainties and then places idle time to improve schedule robustness. In Higgins et al. (1998)[23], an integer programing has been used to create a robust schedule that minimises train delays due to maintenance activities. Louwerse and Huisman (2014)[24] review works of decomposing railway schedules and solve sub-schedules partially. For incomplete sub-schedules, real-time information is used to resolve the incompleteness issue at an appropriate time.

As the level of uncertainty is too high, there is a tendency to perform rescheduling upon arrival of the disruption. Schedulers become reactive and deliver necessary efforts to minimise the size of changes and/or impacts due to a disruption. Occasionally, a scheduler may find an unexpected event triggers small deviations and probably chooses to continue operating the schedule without making any changes. If that is the case, schedulers simply assume that the impacts of minor disruption will be automatically accommodated in a short time and will not affect the remaining operations schedule. Another typical way to repair a schedule from that situation without changing a sequence of remaining operations is by shifting all of the operations altogether to the right on the time axis. For railway applications, shifting the method is almost impossible to be implemented particularly in a timetable because a delay of minutes in all train services would cause chaos in railway stations.

A preferable method of handling disruptions in respect to railway operations is probably a recovery method, also known as a partial reschedule. This method aims to keep a degree of deviation from the existing schedule as low as possible when parts in the schedule that are directly or indirectly affected by disruption are given treatment (rescheduled). In Walker et al. (2005) [25], a cost increment is allowed when doing schedule recovery but it is aimed to keep it small. A vast collection of recovery algorithms can be found in Cacchiani et al. (2014)[21]. Branch-and-bound, mixed integer programming, alternative graph model, genetic algorithm, column generation and heuristic algorithms have been applied in various type of rescheduling problem related to railway. Interestingly, the authors highlight a great challenge of performing recovery on an integration phase (i.e. timetable, rolling and crew schedule). Integrated rescheduling of two resources has succeeded in various studies, such as[26], which uses integer programming.

Periodic schedules can have full-scale rescheduling before the beginning of a next schedules period. This situation normally appears when the existing schedule is no longer feasible for the next application due to the system within the schedule changing vastly. At this point, the literature on scheduling methods, for example in[27], can be revisited to foster new schedule development. Conceptually, repair and recovery methods take less computational effort compared to total rescheduling[16]. In different versions, the use of contingency planning can be seen as an example of total rescheduling. A substantial number of publications regarding contingency plans have been published in the area of resource allocation[28].

Value of rescheduling

A rail inspection schedule comprises of a finite number of (work) trips which consist of a set of all of the movements an inspection team (man and machine) may make in the network. There may be more than one sequence of movements (corresponding to alternative routes) that can define a path through the network. The dedicated schedule *I* is stable if no disruptions occur at any time during an observation period. In other words, no change, amendment or delay will be applied to the schedule. Regardless of the disruption events that lead to rescheduling *I*, the aim is to maximise the value of inspection reschedule *V*. This can be calculated as follows:

$$V(I,\hat{I}) = -\frac{C_r}{w_b \Delta Risk(I,\hat{I})} \tag{1}$$

where C_r is the total cost incurred for rescheduling. A weighting factor $0 < w_b < 1$ is applied to $\Delta Risk(I,\hat{I})$ which represents the size of change in the risk score corresponds to I due to an introduction of updated RIS $\hat{I}$. The factor is introduced to avoid overwhelming the risk of missed oppurtunity.

Costs of rescheduling

In this paper, C_r is formulated as the sum of $\Delta C_{ins}(I,\hat{I})$ and C_p. The first component is a difference in the cost of single type of rail inspection between two RISs; I and $\hat{I}$. For a rail section of length L (in miles) which is expected to receive m inspections, the corresponding inspection cost can be calculated from following function:

$$C_I(m, C_I^d) = mC_I^d + C_I^a = (1+k)mC_I^d \tag{2}$$

where C_I^d is a direct cost per inspection. For a vehicle-based inspection such as ultrasonic inspection train, C_I^d can be estimated from the cost for operating inspection vehicle in which $C_I^d = \frac{L}{\hat{v}_s} c_h$ where v_s is an average speed of the inspection vehicle and c_h is an operational cost per hour per vehicle. As administration elements have important features in scheduling (and maybe rescheduling) rail inspection, the corresponding administrative cost is attached to C_I. For simplicity, C_I^a is set to be proportional to the total direct cost of inspection; kmC_I^d.

There are three types of (administration) activity that could be involved to reschedule I; $W = \{1{:}\,adjust, 2{:}\,cancel, 3{:}\,addnew\}$. For each activity i, $i \in W$, a fraction of administration cost, $c_i k C_I^d$ will be charged as a penalty cost on I. Let n_i be the count of activity i, $i \in W$ required to construct $\hat{I}$, thus, the corresponding total penalty cost can be calculated from $C_p = \sum_{\forall i \in W} n_i c_i k C_I^d$.

Risk of opportunity loss

The risk of missing an opportunity to repair a defective rail before it breaks due to presence of an undetected defect during that period can be calculated as follows:

$$Risk(h_1,h_2) = C_u \sum_{r=1}^{R} S_r N_r(h_1,h_2) \tag{3}$$

The equation is a summation of R risk factors where each factor is a product of the severity of failure, S and the total expected number of broken rails in the periods (h_1,h_2) N multiplied by the potential financial loss C_u. Values of the pair (*S*, *N*) are associated with a type of defect that can lead to a specific rail failure mode. According to the survey in[30], there are eleven risk factors (i.e., causes of failure) associated with rail breaks where transverse/compound fissures and field weld have been found as the major types of rail defects leading to train derailments. Therefore, the parameter *R* has two as its value.

Financial loss

Overlooked or inefficient inspections con-tributes to the increase in numbers in the percentage of undetected rail defects. Some undetected defects may expand or increase to cause the rail to break but the chance of this causing an actual train derailment is less likely. Let $X = \{X_d, X_b\}$ in which X_d and X_b, respectively, denote an event of repairing a detected rail defect and broken rail. When X_b is performed as a result of missed opportunities of X_d, a difference in total cost between these two events, denoted by $\Delta C_{repair}(X_d, X_b)$ could represent a potential financial loss to profit attributed to undetected rail defects. Based on information of repair cost models in Liu et al. (2014)[30], C_u can be formulated as follows:

$$\begin{aligned} C_u &= \Delta C_{repair}(X_d, X_b) \\ &= (C_r^{X_b} - C_r^{X_d}) + \Delta C_{delay}(X_d, X_b) \\ &= (C_r^{X_b} - C_r^{X_d}) + (C_y^{X_b} - C_y^{X_d}) \end{aligned} \tag{4}$$

where C_r^j denotes a total direct cost of rail repair per rail-mile and is a summation of labour, administrative, logistic, machine, tools, machinery and materials cost. The superscript in C_r^j, $j \in X$ indicates the type of rail repair. Similarly, the rule is applied to determine a difference in a delay cost between X_d and X_b, denoted by $\Delta C_{delay}(X_d, X_b)$. The base formula for calculating corresponding cost of train delay for any event in X is given as follows[30]:

$$C_y^j(y, m_1, m_2) = c_o m_1 e^{m_2 y} \tag{5}$$

where y is the number of trains per day on the selected rail line. Values adopted for the delay model parameters; m_1 and m_2 are associated with an event $j \in X$. In terms of train delay, a unit cost (per hour), c_o is invariant with respect to type of rail repair.

Severity

There are a few recommendations regarding the severity value as summarised by Konur et al. (2014) [29]. For example, Zhao et al. (2007) [31] suggested the use of percentage of rail breakage that lead to train derailment. Statistics of broken-rail train derailments provided by Liu et al. (2011)[32] would be a good resource of input for severity estimation. In the event of no changes in the track structure or track operation speed, one can use a constant value (i.e., less than 1) for severity but it might differ as suggested in the previous works[33;34].

Expected number of broken rail

As previously mentioned, we consider that a rail section receives *m* inspections periodically where the corresponding sequence of inspection times are $\langle t_1, t_2, \dots, t_{m-1}, t_m \rangle$. In an arbitrary interval $(t_{j-1}, t_j]$; $j \leq m$ the expected number of rail break due to defect type r may be induced by defects occuring in any interval $(t_{k-1}, t_k]$ where $1 \leq k \leq j$. Since the defects have undergone $j-k$ inspections before they become rail breaks in the interval $(t_{j-1}, t_j]$, the $N_r(t_{j-1}, t_j)$ can be estimated using equation 6[31]:

$$N_r(t_{j-1}, t_j) = \sum_{k=1}^{j} \left(\prod_{i=k}^{j-1} (1 - \beta(t_i)) \times \int_{t_{k-1}}^{t_k} \gamma_r(\tau)[G_r(t_j - \tau) - G_r(t_{j-1} - \tau)]d\tau \right. \quad (6)$$

where $\gamma_r(\tau)$ and $\beta(\tau)$ are the rate of occurrence of defect type r and detection rate at time τ, respectively. Meanwhile, $G_r(\tau)$ denotes the cumulative distribution function (CDF) of delay time corresponding to defect type r. Thus, the expected number of rail breaks occuring to the rail section corresponding to defect type r during the observation period (h_1, h_2) is:

$$N_r(h_1, h_2) = \sum_{j=1}^{m} \sum_{k=1}^{j} \left(\prod_{i=k}^{j-1} (1 - \beta(t_i)) \times \int_{t_{k-1}}^{t_k} \gamma_r(\tau)[G_r(t_j - \tau) - G_r(t_{j-1} - \tau)]d\tau \right. \quad (7)$$

Applying equation 7 in equation 3 gives us the following equation:

$$Risk(h_1, h_2) = C_u \sum_{r=1}^{2} S_r \sum_{j=1}^{m} \sum_{k=1}^{j} \left(\prod_{i=k}^{j-1} (1 - \beta(t_i)) \times \int_{t_{k-1}}^{t_k} \gamma_r(\tau)[G_r(t_j - \tau) - G_r(t_{j-1} - \tau)]d\tau \right. \quad (8)$$

One requires the value of parameter β to operate equation 8. As part of non-destructive testing, an ultrasonic inspection is attached to probability of detection (POD) function. Basically, POD is expressed as a function of defect (flaw) size. While the defect size in terms of the percentage of railhead area $\%HA$ grows exponentially with the accumulated tonnage on track t, thus, the POD(t) function can be written as;

$$POD(t) = a_1 e^{b_1 t} + a_2 e^{b_2 t} \quad (9)$$

where values of model parameter a_1, a_2, b_1 and b_2 may vary by the type of rail defect. Since tonnage of traffic accumulated since the last repair (or renewal) is easily estimated, thus, we have decided to use equation 9 to generate value for β for given t.

Numerical example

The rail network was illustrated on directed graph $G = (Q, A)$ where the set of vertices $Q = S \cup \ O$ corresponds to the set of rail stations $S = \{s_1, \dots, s_n\}$ and the depot O. An arc from vertex i to vertex j is denoted as a_{ij}, $\forall i, j \in Q$. The arc set $A = \{a_{12}, \dots, a_{ij}\}$ where $i \neq j$ includes all available connections between vertices in Q with $|A|$ represents the total number of arcs. Figure 2 depicts a graph representation of (mini) network which has $n = 7$ nodes and $|A| = 12$ arcs considered in this section. Arcs of the sub-network (excluding from/to a depot) were divided into two sets; $SetA$ and $SetB$, based on the inspection requirement for rail flaw detection. In our example, the effects of track length and track layout were not considered when calculating the value of rescheduling.

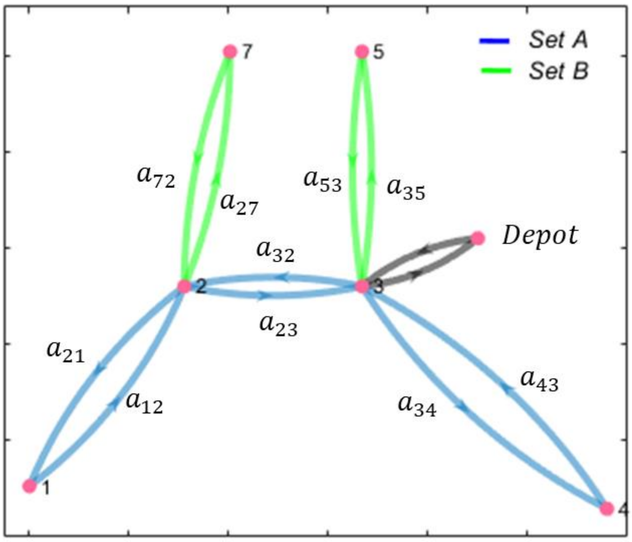

Figure 2: Graph transformation of small instance of typical double rail track line. Effects of track geometry and elevation as well as condition of relevant track components are left out from this example.

Ultrasonic inspection vehicle (UIC) traverses along a rail section to detect internal rail defects. For an individual UIC trip (it will be called trip in the remainder of the text), a set of arcs will be inspected during a track possession interval despite some rail sections not yet requiring inspection i.e. the aggregation approach. Every trip begins and ends at a depot. For the network in Figure 2, there are two default trips; $O - SetA - O$, and $O - \{a_{23}, a_{32}\} - SetB - O$. A collection of the $N = 13$ trips was designed to be performed in the observation period $T = 2$ years and is treated as I, as shown in Table 2.

In the event of no disruptions occur within T, risk score of lossing an opportunity to repair defective rail due to undetected defect for every arc in G under I, is displayed in Figure 3. Table 3 offers values which are extracted from Liu et al. (2014)[30] for calculation of the costs in equation 2,4 and 5. All values to money were converted into present value (in £) based on the time value of fund. Also, the risk calculation was performed based on following considerations:

1. Condition of each rail section is assumed to be nearly new (resulting from a perfect maintenance) at the beginning of T
2. No maintenance or repair works are taking place during an observation period.
3. A sequence of arcs in any trip has no effect in the risk calculation. This is based on the fact that a trip is completed in less than 24 hours due to working-hour regulations.
4. Plot in Figure 3 and 14 in[35] were used for estimation of parameters for POD.
5. Values of parameters for the probability distribution that represent the occurrence of defect and rail

failure were extracted from Patra et al. (2009)[36], and are shown in Table 4.

Table 2 Presumed rail inspection schedule applied on the network G

No.	Trip Date, d_i	Arc $\{a_{12}, a_{21}\}$	$\{a_{34}, a_{43}\}$	$\{a_{23}, a_{32}\}$	Depot	Set *B*
$i = 1$	18/10/18[1]	1	1	1	1	0
2	27/12/18	0	0	1	1	1
3	06/01/19	1	1	1	1	0
4	27/03/19	1	1	1	1	0
5	26/05/19	0	0	1	1	1
6	15/06/19	1	1	1	1	0
7	03/09/19	1	1[2]	1	1	0
8	23/10/19	0	0	1	1	1
9	22/11/19	1	1	1	1	0
10	10/02/20	1	1	1	1	0
11	21/03/20	0	0	1	1	1
12	30/04/20	1	1	1	1	0
13	19/07/20	1	1	1	1	1[3]

[1] An observation period starting from 31/07/18 until 19/07/20
[2] Effected arcs due to a disruption
[3] Final inspection is undertaken on all arcs

Table 3 Summary of cost functions' parameters values

Cost type	Parameter	Value
C_I	k	0.07
	M	1
	v_s	15 *mph*
	c_h	235
C_p	c_1	2.0
	c_2	-0.8
	c_3	5.0
C_r	$-$	£1240(X_d), £1680(X_b)
	c_o	£168
C_d	m_1	1.4714(X_d),3.8643(X_b)
	m_2	0.0352(X_d),0.0349(X_b)

Table 4 Parameterization of function and probability distributions

Function/*pdf*	Parameter	Transverse fissure	Weld (field)
$\beta(t)$	a_1	0.9977	
	b_1	0.000128	
	a_2	-1.325	
	b_2	-0.0752	
$\gamma(t\|\alpha_h, L) = \frac{\alpha_h}{L}\left(\frac{t}{L}\right)^{\alpha_h - 1}$	α_h	2.17	1.01
	L	182.3	315.8
$G(t\|\lambda) = 1 - exp(-t/\lambda)$	λ	8	10

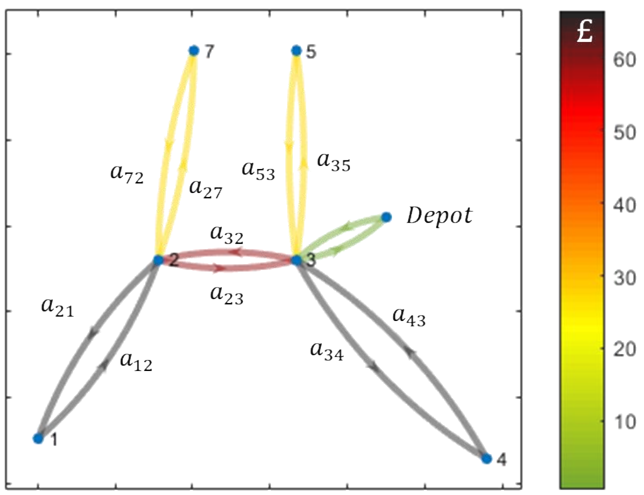

Figure 3: Risk score over G under I. A more frequent inspection resulted lower score in both a_{23} and a_{32} compared to other arcs in *Set B*.

Disruption

Consider that the 5^{th} inspection of $SetA$ scheduled on $(03/09/2019)$ cannot be performed on both a_{34} and a_{43}. This situation implies an adjustment on the corresponding trip which lead to the removal of a_{34} and a_{43} from the the trip no.7. To cope with disruptions, there will be at least possible three rescheduling strategies that may be implemented on the affected arcs.

1. $Strategy1$: No action will be performed and wait for the next inspection scheduled for $SetA$ on $(22/11/2019)$.
2. $Strategy2$: Insert the affected arcs into the nearest trip which is trip no.8. This strategy allows the affected rail sections to be inspected together with a different set of rail section. As a result, an adjustment is required for trip no.8.
3. $Strategy3$: Shift trip no.9 (the 6^{th} inspection times of $SetA$) to the left on time axis; i.e., closer to trip no.6. This strategy will change the inspection policy from periodic to non-periodic but is only applied to the 6^{th} and 7^{th} inspection of $SetA$. A new interval between 1) the 4^{th} and 6^{th} inspection v_{46}, and 2) the 6^{th} and 7^{th} inspection v_{67} of $SetA$ can be determined using the ratio rule given as $\frac{v_{46}}{v_{67}} = \frac{\hat{d}_6 - d_4}{d_7 - \hat{d}_6}$ where $\hat{d}_6$ is a new inspection date of the 6^{th} inspection. For simplicity, $\hat{d}_6$ was rescheduled in the middle between d_4 and d_7. This assignment not only allocates a_{34} and a_{43} with a new inspection interval, but also every arc in $SetA$; $v_{46} = 120$ days instead of 80 days. Importantly, this decision satisfies the condition of inspection interval in Table 1. However, other trips,(particularly trip no.8) are not affected by this strategy.

Results

Figure 3 depicts the effects of possible rescheduling strategies in order to cope with disruptions in the RIS in Table 4. As expected, the risk from a missed opportunity to repair defective rails increases in all proposed strategies. $Strategy2$, among all possible strategies, possesses a little increment in the risk about 2.0 units but it incurs cost, around £ 1.30. Despite penalty administrative fees were also imposed on both $Strategy1$ and $Strategy3$, the strategies generate a refund (shown by a negative reschedule cost). This can be explained by the fact that no reduction in the number of inspection was offered in $Strategy2$ which could be applied to reduce the penalty cost. Comparing $Strategy3$ and $Strategy1$, it appears that the size of refund from trip cancellation has an important role in reducing the penalty administrative fees.

The one with the lowest value of rescheduling is $Strategy2$ in which a decision maker has to spend £ 0.4406 for a unit increment in the risk of missed opportunity. Either $Strategy1$ or $Strategy3$ creates positive decision value. Comparison results show that value of rescheduling is influenced by the number of inspection reduction in I and the selection of new (temporary) inspection interval for υ_{46} and υ_{67}. Keeping the first factor unchanged, sensitivity of the $\frac{\upsilon_{46}}{\upsilon_{67}}$ ratio to value of rescheduling was investigated. In Figure 5, an evolution of value of rescheduling of $Strategy3$ over a range of $\frac{\upsilon_{46}}{\upsilon_{67}}$ ratio values is explained by a Gaussian function. Clearly, optimal decisions in regard to $Strategy3$ is to shift trip no.9 to the left by 20-30 days i.e. 50-60 days after a disruption.

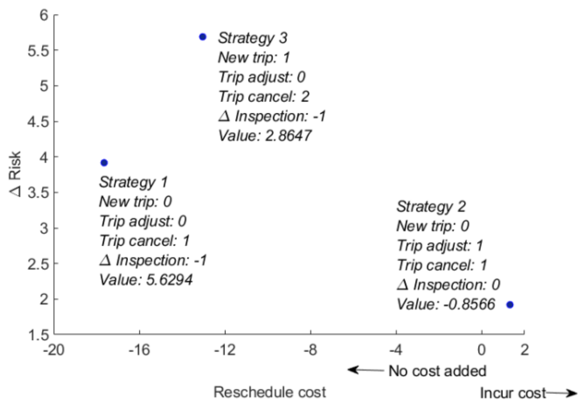

Figure 4: Value of rescheduling from three strategies

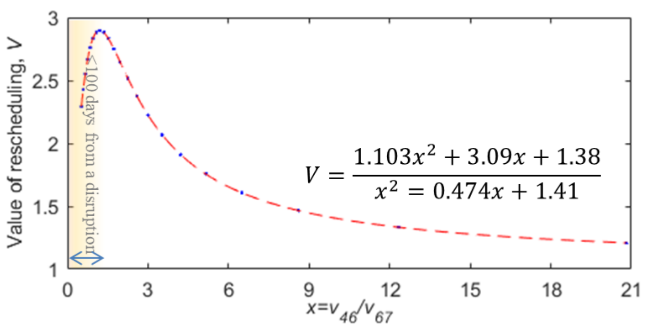

Figure 5: Effects of an interval decision on the value of rescheduling associated with $Strategy3$

Conclusion

Rescheduling would result in allocating such amount of time and resources to ensure that the predetermined schedule can adapt to the impacts of disruption with minimal actions. The situation becomes more challenging for decision makers when several potential rescheduling strategies are presented for a comparison. To support decision makers to effectively conduct corresponding process effectively, this paper proposes a methodology for evaluating (monetary) value of rescheduling for a periodic (on-board) rail inspection. In order to place value on rail inspection reschedule, both costs incurred and benefits that might be gained from the proposed reschedule strategy must be presented. Depending on the type of rail inspection employed, related formulations should be carefully defined. Regarding the rescheduling cost, its value can become negative (a refund) if the provisional schedule changes an inspection policy and cancels scheduled trips. This finding suggests that the demand for external sources of information to convince decision makers to proceed with this type of strategy i.e. not to keep periodicity of predetermined inspection.

The researcher aims to demonstrate the methodology to larger size of railway network. This should help explain how cascade effect could be potentially originated from localised reschedule decisions. As the size of a problem increases, the time taken to execute the proposed methodology is also expected to increase. To accelerate a process of valuation of rescheduling strategies, it is necessary to formulate rail inspection reschedule as an optimisation problem. As different rail sections are attributed with specific operational and safety constraints, the related multi-criteria optimisation model can be expanded to a constrained optimisation model. In addition, the process of determining an optimal interval ratio in $Strategy3$ can be systematically performed by applying the utility function attached to Figure 5. Finally, future work will address the interconnected risk of other rail defects.

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