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Redirecting freight trains: an exact optimization approach

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Abstract

This paper addresses a new problem of redirecting freight trains to revised destinations as a last-minute risk mitigation strategy. The problem is approached from a consignee's perspective as the demand for a change of destination is made by the consignee. An Integer Non-Linear Programming (INLP) model is formulated to minimize the cost of redirecting trains subject to various constraints. The case of a government organization in India which is involved in food grain distribution is considered. The model is solved using commercially available solver and is found to be highly efficient in terms of computation time.

Keywords: Redirecting freight train; INLP; exact optimization; revised destination; risk mitigation

1. Introduction

Railway rescheduling is a well-researched area and active as ever since it opens newer challenges consistently. Rerouting, delaying, and cancelling scheduled trains are common strategies adopted to mitigate the disruptions encountered in railway systems. Most of the literature on railway rescheduling address the problem from a rail operator's perspective. Motivation for this work stems from the need for redirecting freight trains to revised destinations on a real time basis, as demanded by the consignee.

This paper considers the real case of a Government organization involved in massive movement and storage of food grains across India. On an average, 40 to 42 Million Metric Tons of food grains are transported annually within its own storage warehouses and around 85% of these stocks are moved by Indian railway, the sole carrier available for rail transportation in the country. The overall movement plan is prepared on a monthly basis, anticipating the availability of storage space at warehouses. However, it is challenging to follow this pre-specified plan since the outflow of food grains from these warehouses face delay due to various issues in the downstream stages of the supply chain. This results in the unavailability of storage space at the time of arrival of the new shipment. In addition,

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inflexible nature of the labour system employed at warehouses to unload the grains also pose a threat to the smooth functioning of the system. These issues result in the detention of railway wagons (with food grains) at warehouses without getting unloaded and incur additional penalty cost for the organization. Hence, as a last-minute risk mitigation strategy, the train carrying food grains is redirected to another warehouse where it can be unloaded.

Indian railway offers the provision for redirecting freight trains on real-time basis and it involves two options namely interception and rebooking. Interception corresponds to redirecting the train to a destination ahead of the pre-specified destination such that no additional movement of the train is required. Hence, no extra cost is incurred in this case. Rebooking pertains to redirecting the train to a new destination which requires a further movement of the train as compared to the pre-specified plan. As a result, an additional cost called rebooking cost is incurred. Consequently, the first preference is to intercept the train since it involves no additional cost for the organization and rebooking is contemplated only when interception is found infeasible. This paper formulates an Integer Non-Linear Programming (INLP) model to minimize the rebooking cost for redirecting freight trains to revised destinations.

Time of decision making is an important factor in railway rescheduling problems and same is the case in the problem considered in this paper. A delay in decision making can rule out an opportunity for interception of the train (if the train surpass a potential destination for interception by the time the decision is taken), thereby limiting the available option to rebooking, which incurs an additional cost. The time aspect is taken into consideration during model formulation and the proposed INLP model is capable of giving optimum solutions within a short computation time using a commercially available optimization solver. However, the problem limits itself to consider a single route at a time and the availability of storage space as the sole criterion for selecting a warehouse as the potential destination for redirecting the train.

The work presented in this paper distances itself from the conventional train rerouting problem since the pre-specified destination needs to be changed. Also, the decision to redirect the train is made by the consignee due to the inconvenience at the pre-specified destination. Hence, the problem is approached from a consignee's perspective rather than an operator's perspective. The model proposed in this paper provides the consignee firm with a least cost plan for redirecting freight trains. However, it is to be noted that the constraints imposed by the railway carrier is also taken into consideration during the redirecting process, making it more interesting. Thus, the current work caters to the need for development of accurate models and solution techniques for rail traffic management from a consignee's perspective.

The novelty of the work lies in the fact that a new problem of redirecting freight trains is being addressed in a scientific manner. The model extends its practical applicability to firms with multiple warehouses which use rail transportation for moving goods. From an industrial perspective, the simplicity of the model adds to its relevance as a last-minute risk mitigation strategy since exact solutions can be derived readily using commercially available solvers. Since this paper addresses a new problem, a comparative study of the model results with the results from benchmark problems is not possible. However, the model results have been approved by the stakeholders involved in decision making.

The remainder of the paper is organized in five sections. Section 2 provides a review of literature in the domain of railway rescheduling. Section 3 describes the problem in greater detail and Section 4 formulates the problem. Computational study and the subsequent analysis of results are presented in Section 5. Section 6 concludes the work with the scope for future research.

2. Literature Review

The current work focuses on a new problem which involves redirecting freight trains to revised destinations on a real time basis. The authors are unable to find literature that is directly linked to the problem and hence literature published in the related domain of railway rescheduling is reviewed in this section.

Cacchiani et al. (2014) provide a review of recovery models and algorithms used for real-time railway rescheduling. The paper reports that the area has attracted active research interest in recent years. It also projects the pivotal role of Decision Support Systems based on such models and algorithms in improving the reliability of railway systems. The rest of the literature review is arranged in five subsections by grouping similar works together.

2.1. Railway time table rescheduling

Railway time table rescheduling specifically concerns managing passenger train operations to minimize the difficulties for passengers. Louwerse and Huisman (2014) address time table adjustment of passenger railway operator in case of major disruptions. The article proposes an Integer Programming formulation with an objective to maximize the service level offered to passengers. In a similar direction, Binder et al. (2017) address a railway timetable rescheduling problem with multiple objectives which include passenger satisfaction, operational cost and deviation from the original timetable. Wang et al. (2014) present a decision support framework for a high-speed railway timetable rescheduling problem to mitigate speed restrictions and Dollevoet et al. (2017) describe the application of an iterative framework for rescheduling timetable, rolling stock and crew using existing models and algorithms.

2.2. Decision Support Systems for rail traffic management

Curchod (2002) raises concern over the large amount of time lost by international trains, especially freight trains, because of waiting for resources and other administrative tasks. The article presents the concept of the project named OPTIRAILS for optimizing the rail traffic management system in Europe. The implementation of a real-time rail traffic management system named ROMA (Railway traffic Optimization by means of Alternative graphs) is described by D'Ariano et al. (2008). More works related to the application and improvements of ROMA are reported in the following years. Corman et al. (2010) address train conflict detection and resolution problem and propose algorithmic improvements to the Tabu search scheme employed in ROMA. Corman et al. (2011) propose further improvements to the train dispatching model and solution algorithms which form the base of ROMA. The article by Zaninotto et al. (2013) also presents a Decision Support System for train scheduling and rerouting.

2.3. Critical analysis of rail disruption

Determining the root cause of deviation and disruption is essential to formulate a sustainable decision framework for any system. Gedik et al. (2014) investigate the consequence of disruptions in rail networks and thereby determine the elements critical to the network. On similar grounds, Lee et al. (2016) formulate a model for discovering the root causes of delay in railway operations.

Rail track is a critical element of the rail infrastructure and its effective utilization is instrumental in ensuring the smooth operation of railway systems. Gafarov et al. (2015) address railway scheduling problem with single track and two stations. In a similar work, Meng and Zhou (2014) propose an integer programming model for simultaneous rerouting and rescheduling of trains on an N-track network. Further, recent works reported by Ghaemi et al. (2018a) and Ghaemi et al. (2018b) contemplate short-turning trains at a nearby station to mitigate blockages.

2.4. Delay management and building resilience into the railway system

Efficient delay management and building resilience into the railway system are other areas that have attracted research interest. Dollevoet et al. (2012) propose an Integer Programming formulation for the Delay Management problem of trains by incorporating passenger rerouting process. Further, an Integer Programming model to minimize the number of train services cancelled or delayed due to disruption is proposed by Veelenturf et al. (2015). Narayanaswami and Rangaraj (2013) also try to tackle the delay encountered due to disruptions in the rail network.

Hosseini and Barker (2016) rather focus on the aspect of resilience and they model infrastructure resilience as a function of absorptive, adaptive and restorative capacities using Bayesian networks. The paper reports the shift in research focus from preparedness planning (for preventing disruptions) to a mitigation-based philosophy with emphasis on timely recovery actions.

2.5. Time perspective of decision making in railway rescheduling

Fischetti and Monaci (2017) present a Mixed-Integer Linear Programming technique with ad-hoc heuristic preprocessing for real time train scheduling. The article emphasizes the need for obtaining solutions within a short time period to coordinate recovery actions effectively. Kersbergen et al. (2016) also give importance to the time aspect. Sato and Fukumura (2012) present yet another problem associated with the domain of railway rescheduling. The paper considers a real-time freight locomotive rescheduling problem to mitigate disruptions encountered during daily operations. The work also considers the time aspect of decision making.

2.6. Summary

The literature on railway rescheduling indicate the pervasive nature of disruptions and delays in the rail system and the deep impacts they have on the reliability of the system. It can be observed that a larger share of literature on railway rescheduling deal with passenger train operations due to its direct effect on the well-being of customers. However, rail disruptions and delays also have a significant economic impact on freight transportation and the associated stakeholders. This demands greater research attention on freight train rescheduling and the economic impact it has on the operators and consignees. It is also noteworthy that the railway rescheduling problem has been approached only from the operator's perspective, thereby ignoring the scope for a creative engagement from the consignee, in case of freight transportation. Further, the literature review also reveals a clear gap in terms of research since the problem of redirecting freight trains has not been addressed till date. The problem of redirecting freight trains goes beyond the real-time train scheduling problem addressed in literature, since it involves the selection of a suitable revised destination and associated constraints. The observations made from the review of literature indicate the need to develop a time efficient mechanism to address the problem of redirecting freight trains on a real-time basis. This paper proceeds in this direction.

3. Problem description

The problem addressed in this paper deals with redirecting freight trains on a real time basis, as demanded by the consignee firm. A model which minimizes the operational cost incurred for redirecting trains is formulated subject to various constraints. The two scenarios called interception and rebooking associated with the problem are detailed in this section.

3.1. Interception and rebooking of freight trains

Interception and rebooking of freight trains pertain to redirecting trains planned to a particular warehouse to another warehouse (both warehouses owned by the consignee firm) due to unfavourable conditions that exist at the pre-specified destination. The decision for interception or rebooking is taken while the train is in transit and due to the development of unanticipated issues at the pre-specified destination. The revised destination to which the train is to be redirected is determined considering the availability of a suitable destination and the additional cost incurred for redirecting the train.

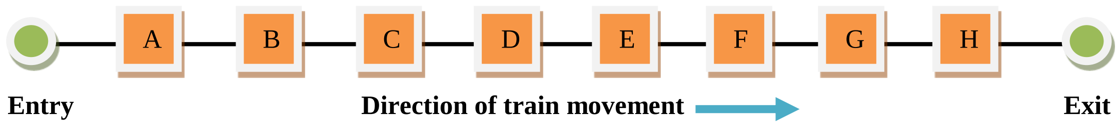


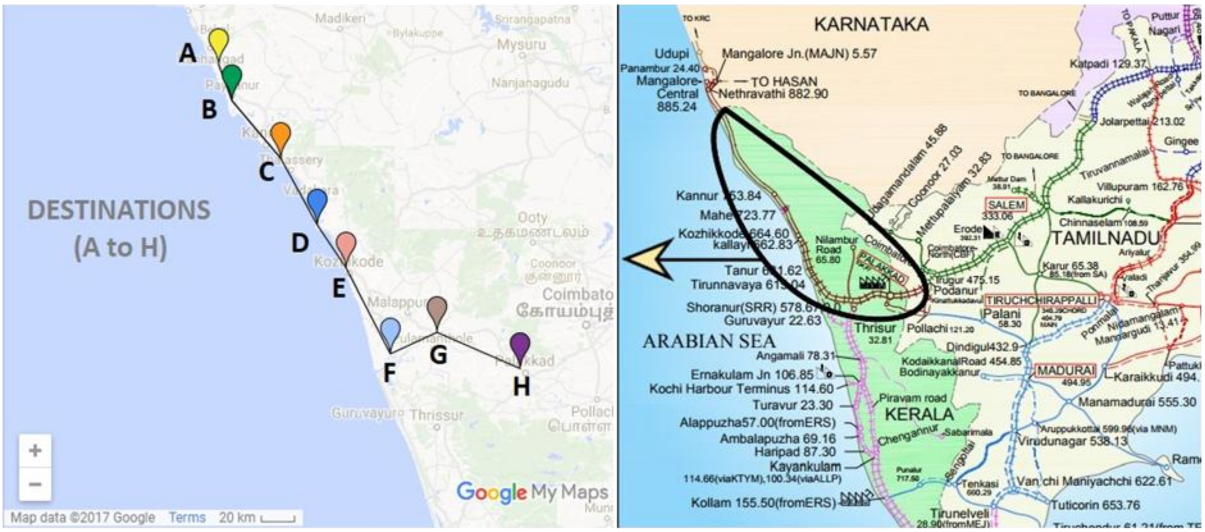
Fig. 1. (a) Set of destinations arranged in the order they are approached by the train

Fig. 1. (a) represents a set of destinations arranged in the order the train approaches them during the inward journey to a region and Fig. 1. (b) indicates the geographical location of warehouses owned by the organization under consideration. The precedence of destinations is an important factor in the context of interception and rebooking. The route is pre-defined in each problem instance as the order of destinations may vary if the train is travelling along another route. As shown in Fig. 1. (a) and Fig. 1. (b), the train approaches the destination A first, followed by B, C and finally reaches the destination H. The various scenarios that may arise in a practical context are explained as follows:

Scenario 1: Interception

Interception refers to redirecting the train (in transit) to a revised destination located ahead of the pre-specified destination before the train crosses the revised destination. A reverse movement of the train is thus avoided as the decision for interception is taken before the train passes the revised destination. Extra costs are not incurred as there is no requirement for additional movement of the train with respect to the pre-specified movement plan. In fact, the traveling distance is shortened.

Interception is the most preferred risk mitigation strategy as no extra cost is incurred in this scenario. The necessary condition for interception is the availability of a suitable destination ahead of the pre-specified destination. In this work, availability of storage space is the only criterion considered for finding a suitable destination. Time of decision making is another important factor. Even when a suitable destination is available ahead of the pre-specified destination, a delay in decision making can lead to a situation which demands a reverse movement of the train incurring an additional rebooking cost.



Source: System Map, Southern Railway

Fig. 1. (b) Geographical location of warehouses owned by the organization

A typical interception scenario is illustrated in Fig. 2. According to the pre-specified plan, the train is to serve destination H and it can be seen that it is positioned at or ahead of destination B when the decision for interception is taken. Destination E is chosen as the revised destination at which the train is to be intercepted, thereby eliminating the need for any extra transportation with respect to the pre-specified plan. Hence no additional cost is incurred in this scenario.

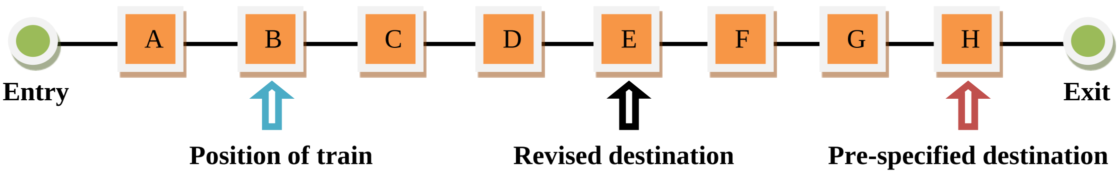


Fig. 2. Interception of a train

Scenario 2: Forward Rebooking

Rebooking is contemplated when there is no chance for an interception. Rebooking to a forward destination involves redirecting the train (in transit) to a revised destination which is located beyond the pre-specified destination. In this scenario, the train should travel an additional distance, and this incurs an extra cost known as the rebooking cost. The rebooking cost depends on the extra distance the train travels with respect to the pre-specified plan. Fig. 3. shows the scenario corresponding to forward rebooking. The train is positioned at destination B when the decision regarding rebooking is taken. The pre-specified destination is E and it is decided to rebook the train to a forward destination H, which comes after E. The additional movement of the train from the pre-specified destination E to the revised destination H incurs an extra rebooking cost.

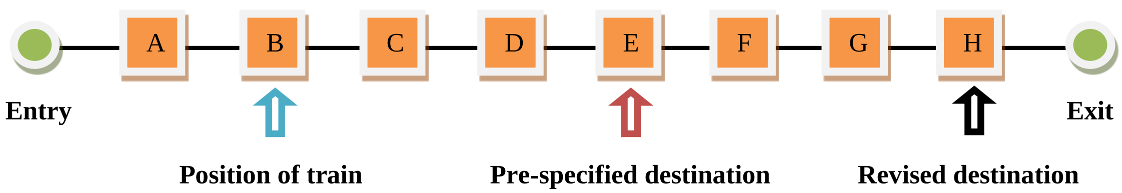


Fig. 3. Rebooking to a forward destination

Scenario 3: Backward rebooking

The scenario of backward rebooking differs from interception as the decision for redirecting the train is taken after the train passes the revised destination to which the rebooking is planned, thus demanding a reverse movement. Fig. 4. represents the scenario of backward rebooking. The train pre-specified to destination G is rebooked to destination A after the train has passed the revised destination A, thus demanding a backward movement. The position of the train at the time of decision making is given as destination D. The scenario would have been an interception if the decision was taken before the train passed destination A. Thus, a delay in decision making leads to additional difficulties and costs.

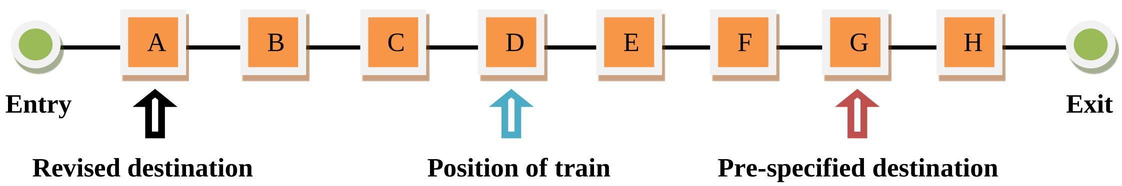


Fig. 4. Rebooking to a backward destination

3.2. General setting of the problem

The consignee organization considered in this work plans the movement of food grains in full rakes (full train load) or a combination of two half rakes (half train load) to avail the associated quantity discount. Hence, the movement plan consists of either a full rake allocation to a single destination or the allocation of two half rakes to two different destinations which originate as a single shipment from the source and gets split en-route. The process of redirecting these rakes is also done in line with the existing conditions. Full rakes are redirected only as a single unit and in the case of redirecting half rakes, there are two possibilities. The first option is to redirect the allocated half rakes to two revised destinations while the second option is to combine them and redirect to a single revised destination as a full rake. The distinction is made based on the feasibility of a particular option and economic considerations. Other assumptions included in the model are listed as follows:

- Availability of storage space is the only criterion for finding a potential destination for redirecting food grain rakes

- Forward and backward rebooking are given equal preference
- The rebooking plan does not coincide with the normal movement plan to a destination

4. Problem formulation

The mathematical model formulated for the problem of redirecting freight trains to revised destinations is presented in this section.

4.1. Mathematical model

An INLP model is formulated to find the destination(s) to which the food grain rakes are to be redirected to minimize the cost involved. The model prefers interception over rebooking since no additional cost is incurred. Rebooking is contemplated only if interception is infeasible. In case of rebooking, the model suggests a rebooking plan that minimizes the rebooking cost.

The set of destinations to which the rakes are pre-specified is represented as S = {S1, S2}. The number of elements in the set S depends on how the initial shipment is booked. The set S will have two elements if the initial booking consists of two half rakes and will contain only a single element if the initial booking is for a full rake. For the rebooking scenario, the set S represents the pre-specified destination from where the rebooking is done. The set of revised destinations to which the rakes are rebooked or intercepted is represented as W = {W1, W2,..}.

Input Parameters

prc_j	the precedence of destination $j \in W$
st_j	storage space available at destination $j \in W$
rc_{ij}	rebooking cost (per wagon) from the pre-specified destination $i \in S$ to the revised destination $j \in W$, in US Dollars (USD)
cp	position of the train at the time of decision making expressed as the precedence value of destinations
wcc	carrying capacity (in Metric Tons) of a railway wagon.
s_i	number of wagons allotted to pre-specified destination/s $i \in S$
br	number of wagons that constitute a full rake
mw	minimum number of wagons that should be allocated to a destination

Decision variables

w_{ij}	number of wagons allotted from the pre-specified destination $i \in S$ to the revised destination $j \in W$ (non-negative integer)
fp_{ij}	integer variable which takes the precedence value of the revised destination $j \in W$ if w_{ij} is positive and zero otherwise
pr_{ij}	binary variable which takes the value 1 when the precedence value of the pre-specified destination $i \in S$ is greater than or equal to the precedence value of the revised destination $j \in W$ and zero otherwise
bin_{ij}	binary variable which takes the value 0 when the redirection process corresponds to interception and 1 otherwise

Objective Function

Minimize:

$$\text{Rebooking Cost} = \sum_{i\in S}\sum_{j\in W} bin_{ij} \times (w_{ij} \times rc_{ij}) \quad (1)$$

Subject to the following constraints*:*

Capacity constraint for destinations: $$\sum_{i\in S} w_{ij} \times wcc \le st_j \quad j \in W \quad (2)$$

Constraint to ensure the complete allotment of wagons redirected from each pre-specified destination:

$$s_i = \sum_{j\in W} w_{ij} \quad i \in S \quad (3)$$

Constraint to set the value for the integer variable fp_{ij} : $$fp_{ij} = \begin{cases} prc_j & if\ w_{ij} > 0 \\ 0 & otherwise \end{cases} \quad i \in S,\ j \in W \quad (4)$$

Constraint to set the value for the binary variable pr_{ij} : $$pr_{ij} = \begin{cases} 1 & if\ prc_i \ge prc_j \\ 0 & otherwise \end{cases} \quad i \in S,\ j \in W \quad (5)$$

Constraint to set the value for binary variable bin_{ij} subject to whether the redirection process is an interception or rebooking:

$$bin_{ij} = \begin{cases} 0 & if\ cp \le prc_i \ \&\ cp \le fp_{ij} \ \&\ pr_{ij} > 0 \ \&\ w_{ij} > 0 \\ 1 & otherwise \end{cases} \quad i \in S,\ j \in W \quad (6)$$

Constraint to avoid redirecting the rake when storage space is available at the pre-specified destination:

$$w_{ij} = s_i \ if\ st_j \ge s_i \ \&\ rc_{ij} = 0 \quad i \in S,\ j \in W \quad (7)$$

Constraint to ensure that the total number of wagons constitute a full rake: $$\sum_{i\in S} s_i = br \quad (8)$$

Constraint setting the minimum number of wagons that should be allocated to a destination:

$$w_{ij} \ge mw \quad if\ w_{ij} > 0 \quad i \in S,\ j \in W \quad (9)$$

The objective function (1) minimizes the cost incurred for redirecting the rakes to the revised destination. The binary variable ensures that no cost is incurred if the redirection process corresponds to interception. Constraint (2) takes care of the availability of storage space at the revised destination and constraint (3) makes sure that all the wagons destined to the pre-specified destination are redirected to a revised destination. The latter also avoids redirecting the wagons from a single pre-specified destination to multiple destinations. Constraints (4), (5) and (6) set the values for the variables fp_{ij}, pr_{ij} and bin_{ij} respectively. Constraint (7) avoids redirecting the wagons to a revised destination if adequate storage space is available at the pre-specified destination. Constraint (8) ensures that the total number of wagons allotted to the pre-specified destination constitute a full rake. The final constraint (9) corresponds to the minimum number of wagons that should be allocated to a destination as stipulated by Indian railway.

5. Computational study

The formulated model is verified by means of computational experiments carried out using the following sets of problem instances:

- Set I: Problem instances are designed to represent various scenarios that are probable with respect to the context of the problem
- Set II: Problem instances are intended to investigate the complexity of the model in terms of computation time.

The computational study is performed on a machine with Intel Pentium Core i3 2.40 GHz CPU with 4GB RAM using the commercially available optimization software ‘AMPL’. The non-linear solver named ‘Gecode’ capable of accommodating logical constraints is employed with it.

5.1. Design of problem instances

The initial set of problem instances consist of eight destinations arranged in the order they are approached by a train following a particular route. The destinations are named A to H and each destination is assigned a precedence value in accordance with its position as shown in Table 2. The available storage space at various destinations and the position of the train at the time of decision making are the important parameters involved in the model. These parameters are varied in order to generate hypothetical problem instances representing various practical scenarios. The rebooking cost between destinations is taken from the online freight calculator provided by Indian railway (Freight Calculator, Indian railway). The values of parameters used in the computational study are provided in Tables 1, 2 and 3.

Table 1. Values of common parameters

Common Parameter	Value
Carrying capacity of a railway wagon (wcc)	62 Metric Tons
Minimum number of wagons that should be allocated to a destination (mw)	10
Number of wagons that constitute a full rake (br)	58

Table 2. Precedence values and available storage space at destinations

Destination	Precedence value (prc_j)	Available storage space (in MetricTons) (st_j)
A	1	3888
B	2	6222
C	3	2902
D	4	15176
E	5	7225
F	6	3453
G	7	6708
H	8	21308

The position of the train at the time of decision making (cp), the pre-specified destination(s) of the train and the storage space available at these destinations are the parameters which are altered to generate various problem instances. Initially, the data corresponding to the opening balance at various warehouses (as on 1st June 2017) of the organization is taken as the available storage space as given in Table 2. The pre-specified destinations and cp value for each instance is randomly chosen and the value of storage space at these pre-specified destinations are altered, if required, to create a need for redirecting the train. The values of available storage space at remaining destinations are kept unaltered. This method is followed to keep the problem instances closer to the real case scenario.

The second set of 15 problem instances aimed to study the computational complexity of the model is divided into three groups of five instances each. Problem instances with more number of destinations are considered for the purpose. The first, second and third group of instances involve 12, 16 and 20 destinations respectively. The average values of computation time for each of these groups of instances are analyzed for obtaining an insight into the practical applicability of the proposed exact solution methodology. In this case, all the parameter values are randomly chosen (except the common parameters given in Table 1) and emphasis is given to study the variation of average computation time with increase in problem size.

Table 3. Rebooking cost (in US Dollars) between destinations

		Destination							
		A	B	C	D	E	F	G	H
Destination	A	0	141.89	149.78	206.97	252.45	316.35	413.93	413.93
	B	141.89	0	141.89	157.65	206.97	282.89	380.58	413.93
	C	149.78	141.89	0	141.89	149.78	252.45	316.35	347.34
	D	206.97	157.65	141.89	0	141.89	157.65	252.45	282.89
	E	252.45	206.97	149.78	141.89	0	149.78	206.97	252.45
	F	316.35	282.89	252.45	157.65	149.78	0	149.78	157.65
	G	413.93	380.58	316.35	252.45	206.97	149.78	0	149.78
	H	413.93	413.93	347.34	282.89	252.45	157.65	149.78	0

5.2. Results and insights

The results of computational study using the first set of problem instances are presented in Table 4. Problem instances 1, 2 and 10 correspond to full rake allocations while the remaining instances deal with half rake allocations. For half rake allocations, the pre-specified destinations are represented (Column 2) one after the other separated by a comma. The storage space at the corresponding pre-specified destinations (Column 3) and the respective revised destinations (Column 5) are arranged in the same order (For example, in problem instance 3, the pre-specified destination for one of the half rakes is A where the available storage space is 1688 MT and it is redirected to the revised destination C. Similarly, the other half rake pre-specified to destination B having a storage space of 1222 MT is redirected to the revised destination D).

From Table 4, it can be observed that the rebooking cost is zero in case of interception of rakes. Problem instances 1, 5 and 9 represent interception scenarios and rest of the instances correspond to rebooking. Among the rebooking scenarios, instances 2, 3 and 4 correspond to forward rebooking (at least one of the two half rakes are rebooked to a forward destination) while instances 6 and 10 represent backward rebooking. Further, problem instances 7 and 8 correspond to a combination of forward and backward rebooking scenarios (one of the half rakes is rebooked to a forward destination while the other is rebooked to a backward destination).

The significance of the position of the train at the time of decision making can be deciphered by a comparison between the following pairs of problem instances:

- Problem instances 1 and 2
- Problem instances 5 and 6

The only difference in input parameters among the problem instances in each pair is the value of *cp*, the position of the train at the time of decision making. In the first pair of problem instances (1 and 2), as the value of *cp* changes from 1 to 6, the scenario translates from interception to rebooking with the incurrence of an associated rebooking cost. It can be observed that the revised destinations are also different. However, in a similar scenario encountered in the second pair of problem instances (5 and 6), as the *cp* value changes from 4 to 5, interception gets converted to a rebooking process although the destinations remain unchanged. These two pairs of problem instances clearly indicate the importance of time of decision making during the redirecting process.

Table 4. Results of Computational Study (Set I)

Problem instance	Pre-specified destination/s	Available storage space at the pre-specified destination/s (in Metric Tons) (st_i)	Position of the train (*cp*)	Revised destination/s	Rebooking Cost (in US Dollars)	Scenario
1	F	3453	1	A	0	Interception
2	F	3453	6	G	8686.95	Forward Rebooking
3	A, B	1688, 1222	1	C, D	8915.33	Forward Rebooking
4	D, E	1800, 1625	4	D, F	4343.47	Forward Rebooking
5	D, E	15176, 1625	4	D, D	0	Interception
6	D, E	15176, 1625	5	D, D	4114.67	Backward Rebooking
7	B, C	1222,1302	2	A, D	8229.33	Combined Rebooking
8	A, H	1688, 1308	1	B, B	4114.67	Combined Rebooking
9	G, H	1708, 1308	1	A, A	0	Interception
10	C	2902	3	D	8229.33	Backward Rebooking

Another interesting aspect of the model can be noted from problem instance 4. It represents a scenario where only one of the two half rakes are to be redirected since storage space is available at one of the pre-specified destinations. As there is adequate storage space available at D, the half rake pre-specified to D is not redirected elsewhere. Nevertheless, the accompanying half rake pre-specified to E is redirected to F, thus resulting in a rebooking scenario. This reveals the capability of the model to ensure that a rake is redirected only if its pre-specified destination is short of adequate space.

In problem instances 5, 6, 8 and 9, it can be observed that both the half rakes are redirected to a single destination due to economic considerations. Thus, the pre-specified allocation of two half rakes to two different destinations gets converted to a full rake allocation to a single destination post revision. This is permissible in the practical scenario and the constraints are set so as to incorporate this flexibility in the model. However, converting a full rake allocation into two half rake allocations is not permitted in real case and such solutions are averted by adding suitable constraints in the model. This is evident from problem instance 10. As per the values of input parameters, the full rake pre-specified to destination C could have been split into two half rakes and one half rake allotted to B or D while retaining the other half rake at C. In that case, the rebooking cost would have been halved compared to the result obtained. But this possibility is ruled out due to the presence of the above mentioned constraint.

The average computation time for solving the first set of problem instances with eight destinations is found to be 0.00245 seconds. This clearly suggests that the proposed exact solution approach is computationally efficient for solving the problem size considered. The second set of problem instances investigates the time efficiency of the solution approach for bigger problem sizes with destinations ranging from 12 to 20. Even in that case, the computation times are found to be within a few milliseconds, well under the acceptable range considering the context of the problem and the time available for decision making. It is observed that the computation time does not show signs of a non-polynomial increase and this averts concerns regarding the computational complexity of the model and the practical applicability of the proposed solution approach. Thus, the formulated model and the proposed solution approach prove its capability to cater to the need for accurate models and solution techniques for rail traffic management.

6. Conclusions and managerial implications

A novel problem of redirecting freight trains in real time is addressed in this paper. Redirecting freight trains to revised destinations correspond to a last-minute risk mitigation strategy to reduce the economic loss due to the detention of railway wagons without getting unloaded. The problem is approached from a consignee's perspective and an INLP model is formulated to minimize the cost incurred for the consignee firm. The case of a government organization in India which undertakes food grain distribution is considered. Computational experiments are carried out to verify the model and to assess its computational complexity. It is found to be computationally efficient and can be solved using commercially available optimization solver within a very short computation time.

Firms which undertake rail transportation of goods within its network of warehouses are the potential beneficiaries of the formulated model. The model suggests a low cost plan for redirecting freight trains if some unanticipated events occur at the pre-specified warehouses. The real time nature of the problem demands quick solutions since any delay in decision making can be costly and further the spread of disruptive effects in the system. The computational efficiency of the proposed model drives away concerns about solution time as it can provide solutions within a short computation time (in the range of milliseconds) for the problem sizes encountered in practice. Thus, the model proves its potential to be the basis of a decision support system that assist decision makers in mitigating risks in rail freight transportation effectively.

Being the first work to address the problem of redirecting freight trains, the model offers a simple framework with only one route being considered at an instant. There is scope for extending this model to incorporate multiple routes which is more challenging. Due to the unavailability of benchmark problems, the validation of the model results is limited to the approval by the stakeholders involved. Furthermore, it is assumed that the redirection plan is not interfering with the normal transportation plan (future deliveries). Future studies can focus on developing an integrated model which deals with both the normal and risk planning scenarios. Also, the model can be tested further with diverse problem instances and bigger problem sizes to assess its effectiveness.

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