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Research Paper

Optimal Increase of Single-Line Railway Route Capacity by Developing a Train Management Schedule Technique

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Abstract

Rail transportation plays a significant role in the movement of commodities and passengers. The progressive demand for transporting passengers and commodities with limited capital available to develop rail infrastructure challenges the rail system ability for transportation by trains. There are two general ways to improve capacity in a route, including new investment in infrastructure and improving the performance of existing lines.

In the present study, time management was used to increase the capacity of existing railways. A new rescheduling model is proposed in this research to overcome some of the current constraints called “Optimal increase in the capacity of lines.” This model uses the conflict solution technique and timetable compaction and can be used for one, two, and multi-line routes. A case study was conducted for part of a single-line BADROOD-ISFAHAN route, in which significant results were obtained.

After process1, more than 25 initial timetable schedule conflicts were resolved in both Same Orders and Order Free approaches. After process 2, the OPTIMAL INCREASE model could compress the timetable by almost one hour and improve maximum dwell times (from 61to30 min) and total dwell times (from 271to168 min) of trains at stations. The total duration of the timetable was increased by almost 20 minutes. After process3, the OPTIMAL INCREASE model provided approximately 36minutes shorter timetable duration (better capacity utilization). Also, the results show that the duration of timetabled developed was slightly increased, mainly due to the sizable reduction in maximum dwell time from 61 minutes to 10 minutes.

Keywords: Optimization, Rescheduling, Timetable, Railway Capacity, Compaction, Level of Service

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1. Introduction

Rail transportation is one of the safest and cleanest ways to transport commodities and passengers. This investigation aimed to improve rail transportation performance [Sadr et al. 2016]. Adjusting the train advance times (the time interval between the start of moving two consecutive trains) is an essential topic for urban railway companies., we have two conflicting goals in this topic, which are (i) the average travel time of passengers and (ii) the wagon filling rate. So far, different multi-objective optimization methods have been conducted to solve this problem, but none have included the objective variance and their correlation in the optimization process.

Hence, this investigation represents a modeling and solution approach based on discrete event simulation and response-level methodology for the problem. It places the average of the objective in the desired area and also tries to minimize their sensitivity to the disorder variables by considering the correlation between the objectives. The results showed the superiority of the proposed approach over previous techniques [Salmasnia et al. 2018].

Effective use of railway capacity means maximizing the number of trains passing through the corridor with maintaining a predetermined Level of Service (LOS). The modeling process can be applied to analyze the capacity. However, configuration differences between railway systems, such as infrastructure ownership and operating philosophy, may lead to applying different methods, techniques, and tools for analysis.

Air transportation is reported to have the highest CO_2 emission per passenger kilometer compared to other modes of travel. Although prior studies have analyzed the impact of high-speed rail (HSR) on the aviation sector, this study is one of the first to develop a simulation model to evaluate the current HSR system and determine the extent to which the existing rail network can handle additional passengers, if short-haul airline customers were to avail of HSR service. This study also proposes recommendations for future HSR schedules and rail capacities. A Define, Measure, Analyze, Design, and Verify (DMADV) approach is developed for (a) conceptualizing the problem, (b) collecting data from different sources, (c) developing the simulation model, and (d) evaluating the results and deriving managerial recommendations. To illustrate the proposed approach, we discuss a case study considering passenger travel between two major European cities, Munich and Paris. It can be observed that the current railway operations between Munich and Paris could only handle 25% of additional customers. If 50%, 75%, and 100% of current air customers were to switch to HSR, then it is recommended to operate one (evening), two (one afternoon and one evening), and three (two afternoons and one evening) additional trains, respectively. Furthermore, this study shows that a complete customer transition from air to rail could save 56.8% CO_2 emissions [Rajendran et al. 2022].

In order to improve the transporting ability of High-speed trains defined the minimizing departure interval between trains and the definition of the drawing compact diagram without considering overtaking conditions. After considering the matching coefficient of train operation, a 0-1 integer programming model was established to maximize the capacity of trains and convert the problem into an asymmetric traveling salesman problem (ATSP). Then an improved algorithm-ant colony optimization (ACO) algorithm is designed to solve the problem. The case of Shanghai to Beijing high-speed trains was an example of solving by programming. Computation results show that considering the matching coefficient of train operation, the optimized scheme can shorten the total time by 219 min (about 28.52%) than the existing scheme [Hao Li et al. 2018].

There are two general approaches for improving the capacity of a rail corridor, the first is to add new capital to infrastructure, and the second is to improve the rail services performance. The everyday use of operating principles without a schedule in the United States has focused most past capacity analyses on identifying and evaluating infrastructure improvements that ensure conflict-free operation. The two key members of a transportation system include direct and continuous communication between passengers and public transportation. It means that any improvement or disruption in the operation of a public transportation system directly impacts travel and waiting time for the passengers. Also, among the parameters that increase pedestrian interest in using public transportation systems, a technique is the reduction of travel and waiting time for passengers.

The efficient scheduling of train running is fundamental to the operational planning of train movement in the passenger-based transportation industry. The timetable determines the availability of transport services across time & space. It also indicates the need for supporting infrastructures like rolling stock, train control systems, traction systems, and workforce. The rationalization of the timetable may profoundly affect the operator's efficiency by optimizing the need for supporting infrastructure. Timetable rationalization in an urban rail transit system is considered with two aims, first is a human intervention to meet the rising passenger demand in ridership. The second is lowering the operational expenditure regarding energy consumption during train operation. A data-based exploratory case study of Delhi Metro line-2 is used to demonstrate the performance of the proposed approach. This paper presents an overview of the initiatives adopted by Delhi Metro Rail Corporation to ameliorate the train schedule and timetable by adopting innovative ways like matching supply with demand, real-time monitoring of demand for necessary intervention in the timetable of the day, coasting or energy-saving mode of operations in Automatic Train Operation, dwell time optimization, and interlacing of high-capacity trains during peak hours [Manish Kumar Sharma et al. 2022].

On the other hand, simulation software is widely used as one of the most powerful and acceptable tools for systems analysis. Various strategies can be simulated and evaluated. In this paper, network components, including city trains, stations, and pedestrian traffic volumes, were simulated using the Emsan and Legion software, and the route from Qeytariyeh station to Shahid Haqqani from Tehran Metro Line 1 was modeled. By creating the model based on the current metro schedules and changing the train schedule, it was found that by considering a time interval of five min, the total waiting time of passengers was reduced by about 15% compared to the current situation. Also, reducing the time interval by one minute (considering four minutes) reduced the waiting time of passengers by 45% [Dehnad et al. 2022].

The potential benefits of further operational changes for European structured operations (based on the timeline) are assessed in rescheduling and schedule management methods [Landex, A. et al. 2006].

For example, in conditions similar to standard European lines, passenger rail services are faster in the United States. Some operational differences can be reduced, and capacity analysis can be more useful in the United States. Many methods and tools are used to evaluate possible improvements in railway capacity, such as analytical methods applied by experienced railway personnel or simulation tools [Lai et al. 2011].

In the present paper, schedule management techniques such as train schedules, schedule changes, and timetable compaction are applied to each type of corridor. However, the complexity of operating a corridor with everyday use (where different types of trains share the same route infrastructure) is more homogeneous with traffic than corridors. Assessing the potential capacity for future traffic or developing a higher quality Level of

Service (LOS) for existing traffic is a reason for rescheduling. Several schedule tools and simulation packages for the railway can be used for rescheduling. However, according to previous studies, no commercial railroad simulation can be identified by (i) solving the automatic train collision and (ii) automatic timetable compaction features to configure various infrastructure and operating patterns. There is a combined approach to solving this case. First, simulation software is used to automate the train collision and create the initial table; then, a software package is automatically used to improve the timetable through the compaction method.

Although this method offers good results but is very time-consuming because it needs to create matching databases in each simulation package, the optimal increase model of line capacity, abbreviated called “Optimal increase model,” is a multi-objective linear scheduling model in this paper for rescheduling at strategic and tactical scheduling levels. The modeling approach increases their capabilities to improve capacity utilization (using timetable compaction technique) or service level (by adjusting train schedule parameters) in a given corridor. The main functions of the optimal increase model are:

1. The model removes all conflicts simultaneously and compresses the initial schedule.
2. This model is applicable for single or multi-line network topologies (one, two, or multi-line) and operational models (directional and two-directs).
3. This model includes flexibility parameters to change the schedule, such as minimum/maximum allowable time and early/late exit time deviation.

2. Literature Review

Since the rail industry began to develop in the early nineteenth century, train schedule/timetable management has been used. Operation rules and schedules ensure the train logical development beside rail corridors and prevent opposing movements between trains. Today, computer tools can help railway planners and distributors with time management and simulation techniques to be more efficient in train operations scheduling and managing. Usually, the train operational characteristic’s evaluation is analytically performed or through simulation, whereas a hybrid approach that uses both analytical and simulation methods is also used.

This paper begins with a brief literature review on rail transportation scheduling and timetable management. However, its primary purpose is to introduce a new stand-alone rescheduling optimization model called “Optimal Increase,” which can be used with any simulation and timetable management tools for rescheduling and timetable compression. The OPTIMAL INCREASE model can be applied to any rail infrastructure (single, double, and multiple route corridors) under directional and non-directional operational patterns.

It can provide a “Conflict Free” and compressed schedule based on the initial timetable and user-defined parameters. This paper describes the OPTIMAL INCREASE model, including its purpose, model concept and application steps, mathematical formulation, and model benefits and limitations. Case studies, each with several processes, are used to test different applications and capabilities of the OPTIMAL INCREASE model in improving or maintaining the results obtained from the software.

2.1. Analytical Applicable Plans

Besides train schedule/optimization in the analytical approach, Timetable management is performed by mathematical equations or algebraic expressions to determine an optimal solution to the problem [Abril, M. et al .2008].

Timetable management, such as train schedule, rescheduling, and a specific type of rescheduling, called timetable compression, are standard techniques to improve timetables to increase capacity and allow for additional trains along a given corridor. This technique selects a route segment for compression of the existing train paths while considering the minimum headway and sufficient buffer times between the trains. After compressing the timetable, new train paths can use the unfertilized capacity until the train paths and buffer times saturate the given period.

Two standard tools that can assist in illustrating timetable management analyses are timetables and string lines. These were developed to present the logical progression of trains along rail corridors soon after rail transportation was established in the early 19th century. The timetable demonstrates the schedule of all trains operated in a given corridor by presenting each train's departure and arrival times at each station and stop point (Table 1). The timetable includes information on three main parameters for scheduling, the train, the time, and the location.

Table 1. Sample Timetable

station	Max. speed	Entrance time	stop train	Departure time
Mashhad	115	-	0	21:20
Salam		21:36		21:36
Fariman		21:49		21:49
Torbat		22:02		22:02
Abumoslem		22:16		22:16
Kashmar		22:27		22:27
Namaki		22:52		22:52
Hesar Jalal		23:11	2	23:13
Kame	90	23:28	0	23:28
Rokh	115	23:41		23:41
Torbat heydarie	110	23:56	5	00:01
Shadmehr	100	00:16	0	00:16

A Graph chart represents the same information as the timetable but is provided in a time distance diagram format (Figure 1). One axis of a Graph diagram typically refers to the "Time," while the other axis refers to the "Location." In this example, the horizontal axis represents time, and the vertical a location. Each sloping line of the diagram shows the movement of one train or other authorized rolling stock over time in both routes. Static trains are shown as a horizontal route.

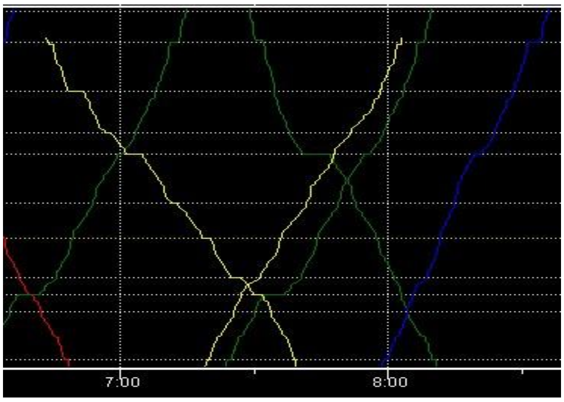


Figure 1. A Sample string line of a single-route corridor

In addition to reviewing the progress of individual train movements, the graph helps identify potential conflicts between trains. For instance, the sloping lines (trains) of a single route in the graph (Figure 1) can only meet each other at legitimate stop points (station and siding and yard); otherwise, it is interpreted as a merge that should be resolute in providing a conflict-free schedule (Figure 2).

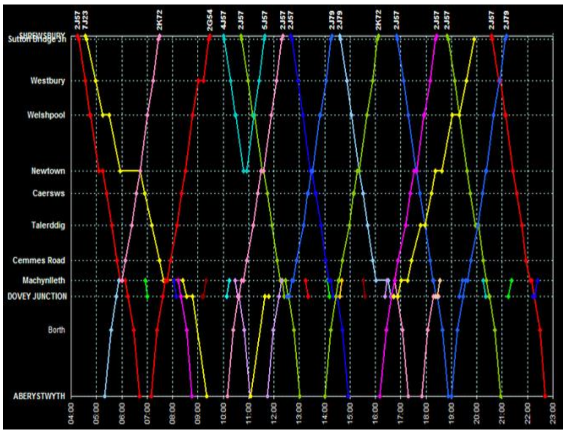


Figure 2. A Sample string line with several train conflicts highlighted by circles

The train scheduling problem can be developed as a Linear Programming (LP) model. The Mixed Integer Programming (MIP) model is a more common method. Because the trains number or periods must be considered integer digits in the model. Some examples of MIP models are ones related to [Kerry et al. in 1991]. More information about optimization models and techniques for train schedules can be found in other literature, such as. Some essential optimization models for train scheduling, rescheduling, and schedule management have been studied [Qusiri et al. in 2004].

A new optimization model based on multi-commodity network flow is proposed for modeling rail routes and capacity calculation. Model inputs are included rail route characteristics and train type. The most important limitations of this model train types limitation and mooring lines number in the stations. The presented model has been used to evaluate the different strategies for increasing the Badrood-Ardakan rail route capacity, one of the country capacity bottlenecks. The model results show that constructing two new nodes and two siding routes between the existing stations based on the capacity increase percentage is the best option [Masoudighini et al. 2011].

A train scheduling optimization model for single-line corridors was developed by Higgins et al. in 1996 based on the first movement time of each train from the origin and the planned arrival time to the destination. A directional route was used for each double-route section and included the scheduled stops model and main line. Model variables included desired arrival and exit times for each train from each station to minimize train delays at the destination and train operating costs [Higgins, A. et al. 1996].

Analytical techniques and models for estimating a line's theoretical capacity based on several criteria such as traffic compounds, crossing points (intersections, joints, sidings), route performance pattern, intermediate signals, line length, trains, and trains stay time at sidewalks or stations were developed by Bordet and Kozan in 2006 [Burdett, R.L et al. 2006].

In, evaluated the real-time timetable flexibility concept in traffic management to improve service accuracy without reducing lines using capacity. They focused more on the investigations on interference resolution between trains during operations by providing more freedom (more flexibility) dedicated to real-time management to improve service disruptions [Dariano et al. 2008].

In 2011, Lindner investigated the timetable compaction method usability (UIC approach) to evaluate the line and station capacity. He concluded that the UIC 406 code acts well when evaluating the main line capacity but may encounter problems when evaluating node station capacity [Lindner et al. 2011].

Another research was conducted by Corman et al. in 2012. They introduced a dual-use conflict resolution problem to minimize the train delays (especially service delays) and lost communications when the rest of the training plan had to be recovered. They applied the joint replacement diagram model to ensure the case study scheduling and developed two innovative algorithms for finding an alternative plan [Corman et al. in 2012].

Sun et al. created a multi-objective optimization model in 2014 for the train routing problem beside train scheduling in China's express rail network. They used an improved genetic algorithm for this problem, considering the average train travel time, energy consumption, and user satisfaction parameters [Sun et al. 2014].

The user to specify where a siding or yard extension is needed to resolve a conflict.

2.2. Timetable Compaction Model

As a general method for rescheduling, the timetable compaction technique is completed in both analytical and simulation methods. That adjusts the train service operational features, which is especially useful for corridors with a predetermined timetable for all daily trains (structured operation pattern).

Most European techniques and tools (from minimal to relatively) depend entirely on timetable compaction techniques. The UIC standard is included for testing and optimizing capacity based on timeline compaction techniques. The predetermined schedule changes by changing in trains’ schedule, in the UIC initial approach, to follow each other as much as possible. Possible new gaps in a timetable created by compressing can be allocated for train additional services or maintenance activities. The steps of the UIC guidelines are shown in Figure 4. In general, there are two methods of rescheduling and compressing of timetable.

However, due to compaction and possible stop-time adjustments, the train order at arrival may differ from the original schedule. The “No Order” (mixed) approach leaves trains based on the user preferences, such as the earliest possible exit time for trains. Train orders may change at both arrival and exit location.

2.3. Simulation Applications

The simulation methods utilize general railway simulation software specifically designed for rail transportation. The rail simulation software can be separated into two categories: Non-timetable and timetable based.

The non-timetable based simulations are usually used by railways based on an unstructured operation pattern without an initial timetable. The timetable-based software is usually used under structured operation philosophy, which is customary. There is much software available in each category, but in this paper, Open Rails represent non-timetable and timetable-based simulation packages.

The results can be used to identify projects that should be investigated further by applying more detailed analysis and simulation tools. The tool requires the development of basic levels of infrastructure, rolling and operation rules (trains schedule) of the given corridor and a conflict identifier within the tool can help.

The UIC compaction technique is based on the same approach. Figure 3 provides an example of timetable compression, where a timetable along a corridor with quadruple Routes (Process a) are first modified by compressing the timetable (Process b) and then further improved by rescheduling or optimizing the train order (Process c). It was shown in the figure that the third process provide a higher level of theoretical capacity in comparison to processes a and b.

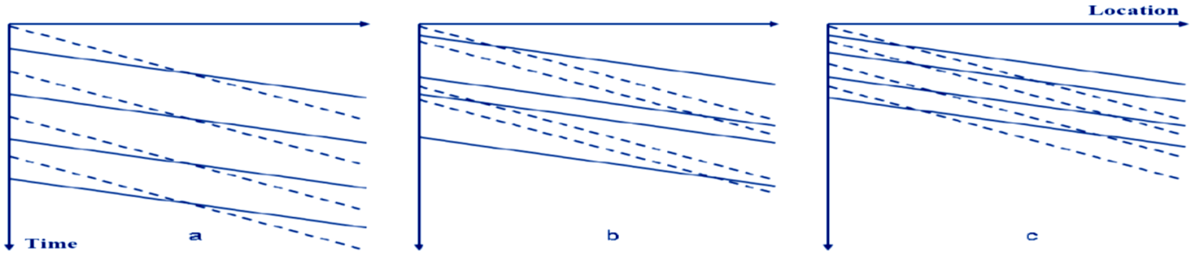


Figure 3. Real timetable for a quadruple route corridor (a) compressed timetable with train order maintained (b) compressed timetable with optimized order (c) (chart layout follows Usual presentation and solid and dot lines represent different types of train

2.4. Reschedule and Compressing Timetable

Usually, there are two approaches to rescheduling and compressing a timetable. The same Order approach retains the train order based on the initial departure times. However, the training request when arriving may differ from the initial schedule due to the compression and potential adjustments in stop patterns. Order Free or shuffle departs trains based on defined user preferences (such as earliest possible departure times of trains). Train orders may be changed in both Exit and arrival locations.

Simulation and timetable management equipped with timetable compression generally follow one of the approaches mentioned above: rescheduling or compression. The UIC compression technique is usually developed based on the Same Order approach, including the timetable compression available in Open Rails.

3. The Generalities of the Optimal Increase Model

According to the previous studies conducted by the authors and as discussed in the literature review, no simulation or timetable management was identified that could address and develop train schedules with 1- automatic conflict resolution and 2- automatic timetable compression technique. A more detailed review and testing of the most common tools (OPEN RAILS) revealed that a more detailed review and testing of the most common tools (OPEN RAILS) revealed that neither of them can address both challenges automatically. A paper presented a hybrid approach where OPEN RAILS was first used to perform automatic train conflict resolution and initial timetable creation. Open Rails was then used to improve the timetable through automatic compression. While this method provided good outcomes, it was time-consuming as it required constructing and matching databases in each simulation package.

The authors believe that a compound of automatic train conflict resolution and timetable compression methods has the potential to comfort and maximize the utilization of the shared-use corridors under development in the IRAN and thus reduce the need for new substruction development. This guarantees the development of a more robust solution to address the limitations mentioned above of currently available tools, further summarized as:

- Many of the existing simulation tools are not equipped with automatic train conflict resolution and timetable rescheduling, and compression
- Simulation and timetable tools equipped with optimization and rescheduling features are usually only valid for single-route corridors under directional operation patterns
- There is no timetable compression model for the IRAN rail environment, such as the E.U models derived from (the International union of railways) UIC timetable compression

The Optimal Increase model, developed as part of this research, is a new analytical standalone model based on the timetable compression that can address the limitations mentioned above by:

- Providing a reschedule and timetable compression model, which can be applied as an additional tool for any simulation and timetable management packages to provide Conflict Free train schedules.
- Developing an optimal model which can be applied for several types of rail case studies, including single, double route, and directional and non - directional operation patterns.
- Developing a timetable compression technique for the IRAN rail environment as well as other regions
- Allowing flexibility to the planner for rescheduling and rerouting trains under different process s.

One multifunctional linear scheduling model for rescheduling is the “Optimal Increase Model.” Table 2 describes the similarities and differences between the optimal increase model and previous models. Another feature of the optimal increase model is the automatic disruption resolution. The optimal increase model is applicable for single-line or multi-line cases (single or multi-line networks). However, the structure of the optimal increase model is designed in this way; it can use directional and two-line patterns for multi-line corridors. This feature is not commonly found in other optimization models [Higgins et al., 1996; Bordet and Kozan, 2006].

Finally, the redirection option by Meng and Zhou (2014) and Sun et al. (2014) is available for the optimal increase model, whereas the redirection decision is not shown as an optimization variable. Instead, the user defines the rerouting option for optimizing the train in the optimal increase model.

Table 2. Similarities and differences between the optimal increase model and other existing models

Difference with the optimal increase model	Similarity with the optimal increase model	Model
Includes additional flexibility parameters such as maximum deviation (flexibility) before and after the requested exit time	Both involve much flexibility	Dariano et al. (2008) and Meng and Zhou (2014)
Various parameters and sub-algorithms of timetable compaction technique The optimal increase model includes similar patterns and no order	All use the timetable compaction technique	Banorect (2005), Dariano et al. (2008), Lindner (2011) and Govorde et al (2014)
Minor interferences due to lack of acceleration/deceleration parameters	Ability to interferences automatic resolve	Zhou and Zhong (2007) and Corman et al. (2012)
The optimal increase model includes directional and two-way patterns for multi-line corridors (single or multi-line networks)	All apply to one-lane or multi-lane corridors	Qusiri et al. (2004), Thornick and Pearson (2007), and Namg and Zhou (2014)
The user determines new lines	Rerouting capability	Meng and Zhou (2014) and Sun et al. (2014)

4. An Overview of the Optimal Increase Model

The conceptual design and methodology of the OPTIMAL INCREASE model presented in this paper is a multi-objective linear programming (LP) model for train rescheduling at strategic and tactical planning levels. It works with existing rail simulation tools, extending their abilities to improve the capacity utilization or the Level of Service of a given rail corridor by applying timetable compression. It should be noted that capacity utilization can be increased by operating more trains simultaneously or by reducing the timetable duration while mainly training the number of trains (timetable compression).

Since the optimization concept of the OPTIMAL INCREASE model is derived from the timetable compression technique introduced by the UIC, capacity utilization is represented in this paper by the timetable duration parameter. Thus, OPTIMAL INCREASE keeps the same number of trains while adjusting the timetable duration of train schedules.

4.1. Optimal Increase Model Methodology

The line capacity optimal increase represented in this paper is a multifunctional linear scheduling model for train rescheduling at strategic or tactical scheduling levels. This model increases the line capabilities to improve the capacity or level of service utilization of a specified corridor by using the timetable compaction method (adjusting train schedule parameters). Capacity utilization can be increased by more operating trains in a similar period or by reducing the period (scheduling) by maintaining the train number (timetable compaction method).

The optimal increase model optimization concept is derived from the timetable compaction method introduced by the International Union of Railways (UIC), so the use of capacity in this study is shown with the schedule parameter. Thus, the optimal increase model maintains the same number of trains by adjusting the train schedules.

The optimal increase model applies the parameters defined by the user, such as movement time flexibility for each train and the allowable stay time at each stopping point. Many attempts are made to minimize the train’s exit time and the deviation between the proposed stay time and the minimum allowable cases. Furthermore, this model can reschedule the different trains based on defined routing designs by the user instead of the current line.

Model outputs include the train exit offer and stay time. Figure 4 shows the steps for using the optimal increase model:

1. Extraction of the initial Schedule from timetable management (A)
2. Creation of the data set in a table based on the initial timetable and parameters defined by the user (such as minimum/maximum flexibility of exit time and stay time and train routing) (B).
3. Performance of the optimization section of the optimal increase model in the solver, LINGO. The optimization outputs contain train exit and stay time within the particular range (C).
4. Updating the exit time and stay time and a possible new line (defined by the user) in the data sheets of Tables (D).
5. Confirm the new exit, new stay time, and line time in a timetable, further analysis, and start a new repeat, as desired (A).

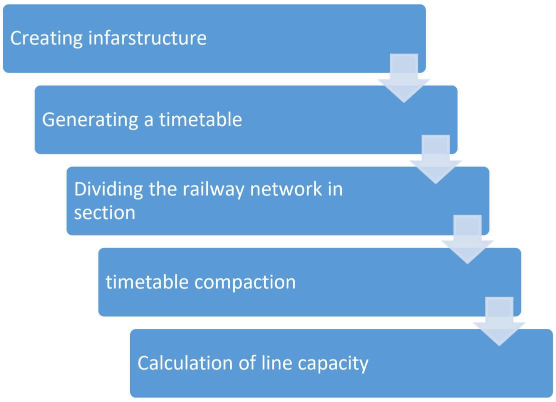


Figure 4. The main steps of optimal increase model performance

Step A (scheduling management tool) is not required to obtain a solution from the optimization section in the optimization increase model (step C). However, it facilitates data extraction and validation of the proposed results. Also, steps B and D are typical database management steps usually carried out in any optimization modeling investigation, either using solver internal features or other external database management tools. The primary role of this research is the optimization of the optimal increase model (step C in Figure 5).

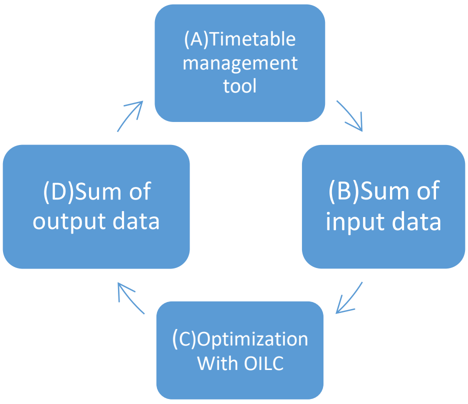


Figure 5. Steps of timetable compaction for the scheduling with the UIC406

Optimization consists of three main components, as shown in Figure 6:

1. Model data and parameters (input).
2. Objective functions and constraints (constraints/expectations).
3. Decision variables (outputs).

The parameters of the level of service in an analysis depend on the research perspective. For example, meaningful parameters for evaluating the optimal level of satisfaction in railway customers/customers may be quite different from parameters that evaluate operational efficiency from the viewpoint of the substructure manager or operator. The parameters of the level of service (listed in Figure 6) in the optimal increase model are defined from the viewpoint of the schedule. They are adjustable by the user if necessary. Two sets of input-substructure models and operation-schedule data are extracted, and train data is commonly developed from the timetable and the user preferences. The optimal increase model decision core uses all model inputs (parameters) to simultaneously resolve all possible conflicts and compress the initial plan (Figure 7). An optimal increase model will minimize the weighting sum of the proposed output times (output) and the deviation between the stationary times (output) and the minimum allowable times.

4.2. Mathematical Formula of the Optimal Increase Model

The ß$_1$ and ß$_2$, a reiterative calibration process, were used to devote the values of "50" and "1" in order. The optimization section in the optimal increase model (component "C" in Figure 5) is formulated as a multipurpose linear scheduling model and can be solved using simple or two-simplex algorithms. The mathematical formula is explained below:

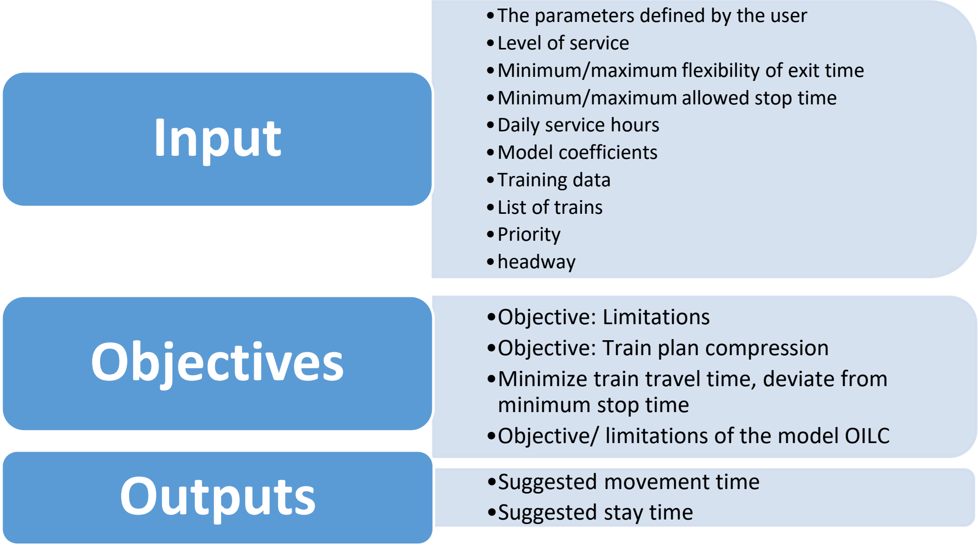


Figure 6. Optimization components of the optimal increase model, including input, objectives/constraints, and output

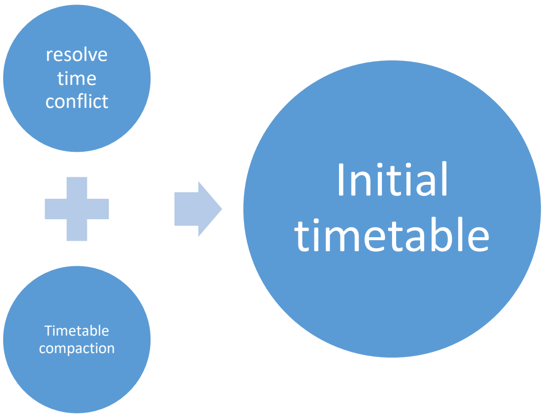


Figure 7. The central decision core for the optimal augmentation model

4.2.1. Parameters and Model Variables

Table 3 describes the data and parameters of the optimal increase model (input) and variables (output).

Table 3. List of optimization parameters and optimization increase model variables

Parameter	Description
SP^{ij}_t	Travel time for train "t" on the assigned route between two consecutive station "i – j" (min or sec)
XDS^i_t	Suggested movement times for train "t" from any station "i" (min or sec) (variable)
CM	Maximum timetable duration (converted to minutes or seconds) CM> 0
MP^{ij}_t	Route number matrix to any train "t" that travels along two consecutive station "i-j"
ß$_2$; ß$_1$	Weighting coefficients of stop time (ß1) and exit time (ß2), ß1, ß2> 0

Parameter	Description
C	A set of station “i” (e.g. station, mooring, store, intersection)
R_t	Route of rain “t”
RT^i_t	Maximum time allowed to stop train "t" at station "i" (minutes or seconds)
P_t	Train priority (should be determined based on the train service quality importance and train scheduling. The higher the train priority, the higher the Pt value)
M (S_t)	Minimum speed for train “t” before movement to another train on the same route. (min or sec)
S	A collection of all trains
MDB^i_t	Maximum acceptable train delay "t" before the requested time from station "i"
O_t	Subset of train origin “t” outside the set
D_t	Subset of train destination “t” out of set
SP^{ij}_t	Travel time for train “t” on the assigned route between two consecutive station “i – j” (min or sec)
MP^{ij}_t	Route number matrix to any train “t” that travels along two consecutive station “i-j”
DS^i_t	Requested movement time (daily hourly/time) for train “t” from station “i” (min or sec)
MDA^i_t	Maximum acceptable train delay "t" after the requested time from station "i"
LT^i_t	Minimum time for train t at station i (min or sec)
XT^i_t	Suggested stop time of train “t” at each station “i” (min or sec) (variable)

4.2.2. Model Objectives

The optimal increase model tries to minimize two values: exit time and stay time deviation. This model compresses train schedules as much as possible. It compresses the train schedules by allowing flexible stay times for meeting and stopping purposes, scheduling movements as soon as possible based on defined priority, permissible flexibility, and requested exit times. The user defines the priority level, but higher-priority trains are generally expected to move sooner and have a less stay time deviation than lower-priority trains. The objective function is presented in Equation 1.

$$MIN \beta_1 \times \sum_t \sum_i \left(XT_t^i - LT_t^i\right) \times P_t + \beta_2 \times \sum_t \sum_i XDS_t^i \times P_t \tag{1}$$

Where ß1 and ß2 are weighting coefficients that indicate the relative importance of stay time versus exit time, respectively, since the numerical values of the fixed time deviation (first part of the function) are much smaller than the train movement time (second part), the user can scale these two parameters depending on the weight preferences. An increase of ß1 allows the user to prioritize the maintenance of desired stay times over the compaction of the new scheduled timetable, as will be discussed later in the sensitivity analysis of coefficients ß1, ß2.

4.2.3. Model Limitations

The optimal increase model has many limitations that can be applied to rescheduling/compaction approaches without order and with the same rank. The sections below provide a detailed description of the model limitations in each approach. Equation 2-11 shows the rescheduling approach limitation in the same way.

Equation 2: The movement time of each train from any stopping point (left) should not be less than the first possible exit time for a given train (right).

$$XDS_t^i \geq DS_t^i - MDB_t^i \qquad \forall t \in T \ , \ \forall i \in C \tag{2}$$

Equation 3: The movement time of each train from any stopping point/station (left) should not be longer than the last possible exit time for a given train (right).

$$XDS_t^i \leq DS_t^i + MDA_t^i \qquad \forall t \in T , \forall i \in C \tag{3}$$

Equation 4: The stopping time of each train must be maintained between the minimum and maximum permitted stay time at each point/station. A train cannot stop at a specific stopping point $\left(XT_i^t = 0\right)$ if the minimum and maximum stopping time is set to 0.

$$LT_t^i \leq XT_t^i \leq RT_t^i \qquad \forall t \in S \ , \ \forall i \in C \tag{4}$$

Equation 5: Total trip time of each train is equal to the sum of line travel times between the origin or destination plus the sum of all dwell times in the stop points or stations.

$$XDS_t^d - XDS_t^o = \sum_j \sum_i SP_t^{ij} + \sum_j XT_t^j \qquad \forall t \in S \ , \forall i, j \in C \ , |i-j| = 1 \tag{5}$$

Equation 6: The movement time of the train from each stop/station point (left) is equal to the movement time of the previous point/station plus the travel time of the previous section of the route and the current stopping time.

$$XDS_t^j = XDS_t^i + SP_t^{ij} + XT_t^j \qquad \forall t \in S \ , \forall i, j \in C \ , |i-j| = 1 \tag{6}$$

Equations 7 and 8: Given the many limitations, there must be a minimum advance or buffer time (right) between movements of two consecutive trains (left). These limitations are written for a subset of trains defined by the following condition, as specified by the model data.

(i). Trains move in one direction $(R_t \times R_p = 1)$

(ii). The exact order of trains is maintained $(DS_t^i \rangle DS_p^i)$

(iii). Train "t" is rather than train "p" $(SP_p^{ij} \geq SP_t^{ij})$ or mutual $(SP_p^{ij} \langle SP_t^{ij})$

(iv). Trains have the same route $(MP_p^{ij} = MP_t^{ij})$

Equations 7 and 8 differ in the order of the slower and faster trains. Equation 7 shows the plans of a slower train that the faster train follows $(SP_p^{ij} \geq SP_t^{ij})$.

Hence, Equation 7 has an additional term on the right of the limitation, showing the excessive time calculated based on the minimum advance of the faster train $(M(S_t))$ and the speed gap between trains $(SP_p^{ij} - SP_t^{ij})$.

Since faster and slower trains are determined by Equations 7 and 8.

The progress defined in Table 3, $(M(S_t))$, considers just the train that moved earlier (the last train).

$$\begin{gathered} XDS_t^i - XDS_p^i \geq M(S_p) + M(S_t) + (SP_p^{ij} - SP_t^{ij}) \\ where\ (R_t \times R_p = 1) \cap (DS_t^i \rangle DS_p^i) \cap (SP_p^{ij} \geq SP_t^{ij}) \cap (MP_p^{ij} = MP_t^{ij}) \\ \forall t, p \in T \ , t \neq p , \forall i, j \in C , |i-j| = 1 \end{gathered} \tag{7}$$

$$\begin{gathered} XDS_t^i - XDS_p^i \geq M(S_p) \\ where\ (R_t \times R_p = 1) \cap (DS_t^i \rangle DS_p^i) \cap (SP_p^{ij} \geq SP_t^{ij}) \cap (MP_p^{ij} = MP_t^{ij}) \\ \forall t, p \in S \ , t \neq p , \forall i, j \in C , |i-j| = 1 \end{gathered} \tag{8}$$

Equation (9): No train can move (left) until the last train reaches the given station in the opposite direction (first and second parts on the right), plus the minimum route between these two trains (third part on the right side). The following condition defines the subset of trains, including these limitations:

(i). Trains move in the opposite direction $(R_t \times R_p = -1)$

(ii). the exact order of trains is maintained $(DS_t^i \geq DS_p^j)$

(iii). Trains have the same route $(MP_p^{ji} = MP_t^{ij})$

Three limitations (Equations 7-9) include parameters MP_t^{ij} and MP_p^{ji} estimating errors for each training pair. If trains use a familiar route, conflict resolution will be activated. This feature, besides train direction evaluation, makes this model applicable to one or multi-line network configurations (one, two, and multi-line) and different operating patterns (directional or two-direction).

The train's order is inherently maintained within these three limitations because examining the train's original orders one of the conditions.

If this condition is met (along with the other conditions described above), a new movement time is recommended while maintaining the train's original order.

$$\begin{gathered} XDS_t^i \geq XDS_p^j + SP_p^{ji} + M(S_p) \\ where\ (R_t \times R_p = -1) \cap (DS_t^i \geq DS_p^j) \cap (MP_p^{ji} = MP_t^{ij}) \\ \forall t, p \in S \ , t \neq p , \forall i, j \in C , |i-j| = 1 \end{gathered} \tag{9}$$

Equation 10: The timetable duration (left) should not exceed the maximum service hours defined by the user.

$$XDS_t^d - XDS_t^o \le CM \quad \forall t, p \in S, d \in D_t\ , o \in O_t \ (10)$$

Equation 11: The proposed exit times and the stay time variable are defined as non-negative absolute values to provide a faster and more reliable solution.

$$XDS_t^i \ge 0\ , XDS_t^i \in real\ ,\ XT_t^i \ge 0\ , XT_t^i \in real \ (11)$$

Although, in theory, it is not necessary to define both exit time and stay time as integer values, we can ensure that these variables adopt integer values by determining integer values for requested exit times, travel time, and minimum/maximum stay times allowed in the model which is due to the structure of the limitations defined by Equations 5 and 6.

Limitations allow changing the trains order as part of the solution to the no-order approach based on the amount of flexibility defined by the user (MDB) included in the limitations. Changing trains in order may provide a higher density level; however, the new plan may also cause a station capacity shortage if many trains try to pass or stop simultaneously.

4.2.4. Model Innovation and Advantages

Based on the structure of the OPTIMAL INCREASE model, it is expected that the model can achieve the following suppositions. The performance of the model against these suppositions was tested by applying the OPTIMAL INCREASE model to case study process s. The results are discussed in the following sections of the paper.

- the capability to reschedule and compress the timetable of different train types on single, double, and multiple route corridors under directional and non-directional operation patterns.
- The capability to provide a Conflict Free train schedule, even if the initially requested schedule has serious conflicts between trains.
- The model can be practical for both Same Order and Order Free schedule approaches based on user preference.

4.2.5. Model Considerations

When using the OPTIMAL INCREASE model, certain limitations should be considered, such as:

- Each stop point or station is considered a single node in the model. Since trains cannot be assigned to various station routes, the OPTIMAL INCREASE model may provide more conservative departure and arrival times at stations. A more detailed simulation of route usage at stations can be conducted in the simulation and timetable management during the validation process. If any train is too long for available routes at a station, the train should not be allowed to stop, making the minimum and maximum dwell time of such train “zero” at the given station.
- The model is susceptible to the requested departure times, flexibility parameters of departure times, and the minimum and maximum dwell times of trains. Reducing the value flexibility of these parameters may prevent the optimization part of the OPTIMAL INCREASE model from finding a feasible solution for all trains. Increased flexibility would be required to allow the solver software to find the best answer for all trains.

5. The Optimal Increase Model Test

Based on the suppositions, several applications of rescheduling and timetable improvement can be carried out by the OPTIMAL INCREASE model. The following sections use single route case studies to examine the OPTIMAL INCREASE model performance on different applications and process s. A comparison between the initial schedule of each case study process and the OPTIMAL INCREASE model results was used to test the capabilities of the OPTIMAL INCREASE model in improving the schedule. The databases for all process s were developed in Excel, and LINGO was used as the optimization Solver.

In comprehensive research for the doctoral thesis, the need for an active route with full capabilities to validate the model seemed to be needed; in this regard, the BADROOD-ISFAHAN route was chosen, including single, double, and multiple lines. In this paper, a part of the mentioned route, a single lane, was studied and tested.

A case study of the BADROOD-ISFAHAN multi-line route, currently applied for passenger and freight trains, was used here. The modeled route followed the existing substructure, while more complex train and signal parameters were developed for the case study.

The case study includes a 50 Km long single route segment with two sidings and a yard for meet and passes and stops purposes. Three types of trains were considered in the case study: Passenger (4 pairs daily or north-south), merchandise freight (2 daily pairs), and intermodal trains (3 daily pairs). There were no planned stops for trains, but trains were allowed to stop at the sidings or yards due to the meet-or-pass concept. The case study had no predefined arrival or departure timetables, although some preferred departure times were defined for each process. Table 4 synopsis the case study parameters.

A single-line case study was designed to evaluate the performance and capabilities of the optimal increase model. This design was performed using an approach similar to the modeling process. The design was performed using the selected no-order approach, and LINGO was applied as the optimization solver. Since the purpose was to provide approximately equal values for the exit time and stay time coefficients (ß1 and ß2), a repetitive calibration process was used to assign the values of "50" and “1”, respectively.

5.1. Case Study of the Single-Line Route

A case study of the BADROOD-ISFAHAN single-line route, currently applied for passenger and freight trains, was used here. The modeled route followed the existing substructure while more complex train and signal parameters were developed for the case study.

The case study consisted of a single 205 km long line with eleven stations for intersection and stop purposes.

There were no scheduled stops for any trains. A summary of the case study parameters is given in Tables 3 and 4. The optimal increase model performance in a single-lane route was investigated (as shown in Table 4).

In this plan, a timetable with several contradictions was used as the initial plan (timetable), and the optimal increase model was used for both the resolution of contradictions and the compaction of the timetable. No same-order patterns are used here.

The MDB, MDA flexibility parameter and maximum allowable stay time were different, while the other flexibility parameters, such as minimum allowable stay time, were the same.

Table 4. Case study infrastructure details

50 km, single line	Section length
3	Station
4 passengers + 3 freight/passenger + 2 freight	Trains
Max. vertical grade	2.12%
Curvature	0.01 - 7.27 degrees
traffic combination (passenger freight)	Type of Traffic
Two sidings + 1 yard	Sidings and yards

Table 5. Stations on the BADROOD-ISFAHAN railway route

No.	Station	Distance to previous station (km)	Distance from station to Tehran (km)
1	Badrood	--	343
2	Jazan	22	365
3	Sepidan	19	384
4	Abyazan	16	400
5	Rangan	23	423
6	Gol	14	437
7	Chariseh	15	452
8	Verton	37	489
9	Sistan	19	508

No.	Station	Distance to previous station (km)	Distance from station to Tehran (km)
10	Firuzeh	21	527
11	Isfahan	21	548

Table 6. Single-line case study plan

Level of assigned flexibility parameters	High
Rescheduling pattern	No Order or Same Order
Tested performance	Training in Conflict Resolution and Compaction
Initial timetable used in each plan	Initial program with multiple interferences (worst case)

The case study was initially developed in simulation packages (OPEN RAILS) to test a combinatorial simulation method for timetable improvement. For OPTIMAL INCREASE testing, three primary processes s were developed:

- Process 1: Using the OPTIMAL INCREASE model to improve an initial timetable with serious conflicts
- Process 2: Using the OPTIMAL INCREASE model to improve an initial Conflict Free timetable (developed by OPEN RAILS) and to evaluate the station capacity limitation of the OPTIMAL INCREASE model
- Process 3: Using compressed timetables developed by Open Rails and OPTIMAL INCREASE model to compare their compression techniques

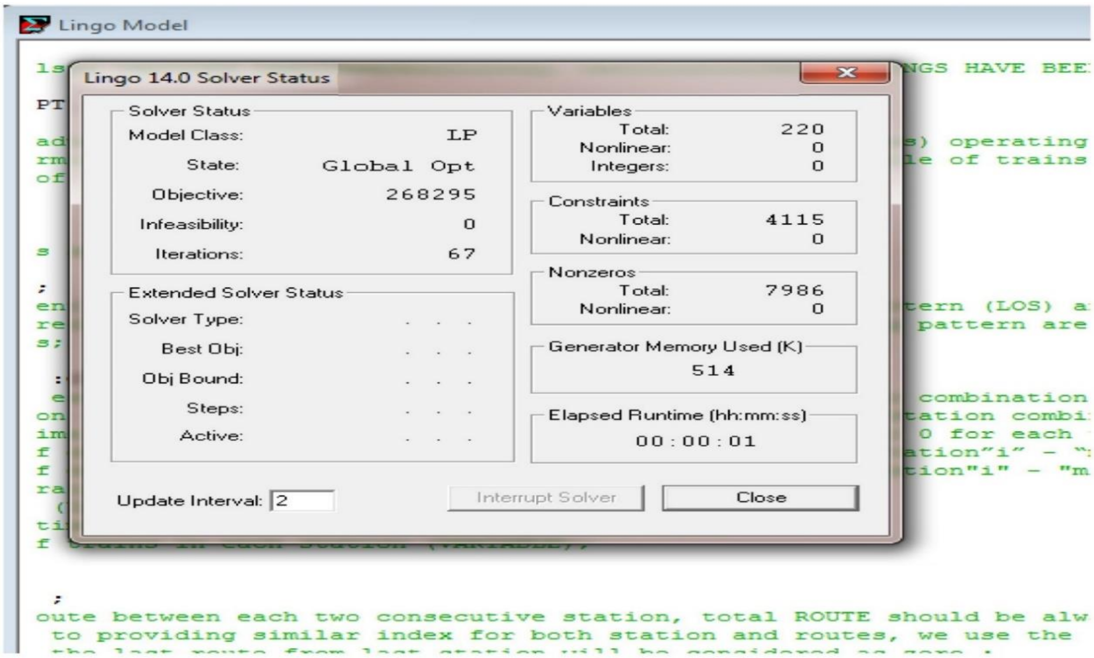
5.1.1. Process 1: Initial Timetable with Conflict

The purpose of this process was to investigate the capabilities of the OPTIMAL INCREASE model to transform an initial timetable with several schedule conflicts (developed intentionally) into a Conflict Free scheduling. Table 7 summarizes the user-defined parameters of the OPTIMAL INCREASE model in Process 1. All parameters of each train category, such as the MDA flexibility parameter, were considered equal through all stations.

After running the model in LINGO, the adjusted departure and dwell times of the improved timetable were generated by LINGO for both Same Order and Order Free approaches, but in separate model runs. The output from LINGO was converted to the (hh: mm) format in Excel sheets for validation in Open Rails. Figure 10 presents the initial timetable obtained from Open Rails for Process 1 (top) and the OPTIMAL INCREASE model results for both Same Order and Order Free approaches (middle and bottom), as validated by Open Rails. More than 25 initial timetable schedule conflicts were resolved in the Same Order and Order Free approaches by providing appropriate meet or pass stop patterns for train trains at the stations.

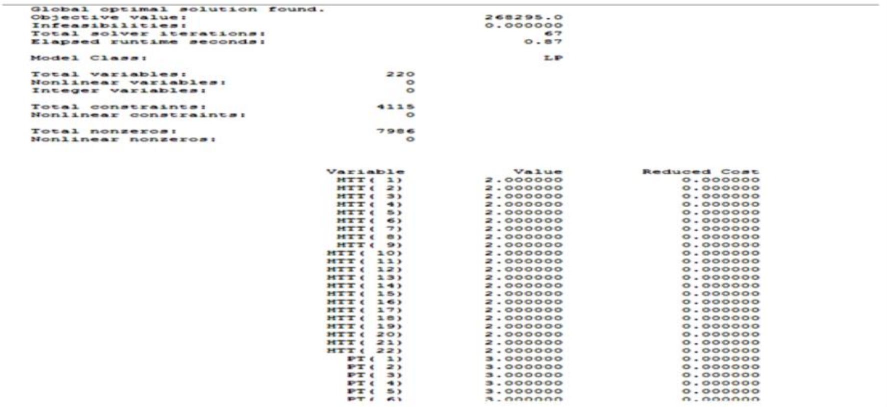
Table 7. Details of defined parameters for the OPTIMAL INCREASE model to solve process 1 (timetable with conflicts)

Criteria	Passenger	Intermodal	Freight
Minimum allowed dwell time(minute)	0		
Maximum allowed dwell time(minute)	10	20	60
MDB(minute)	0	90	60
MDA(minute)	240		
Headway(minute)	2		
Priority	3	2	1



```
Solver Status
Model Class:            LP
State:          Global Opt
Objective:          268295
Infeasibility:           0
Iterations:             67

Extended Solver Status
Solver Type:
Best Obj:
Obj Bound:
Steps:
Active:

Update Interval: 2

Variables
Total:        220
Nonlinear:      0
Integers:       0

Constraints
Total:       4115
Nonlinear:      0

Nonzeros
Total:       7986
Nonlinear:      0

Generator Memory Used (K)
514

Elapsed Runtime (hh:mm:ss)
00:00:01
```

Figure 8. the shot of the optimum solution found by Lingo after solving the single route case study based on the OPTIMAL INCREASE model (Process 3)



```
Global optimal solution found.
Objective value:                                  268295.0
Infeasibilities:                                  0.000000
Total solver iterations:                                67
Elapsed runtime seconds:                              0.87

Model Class:                                            LP

Total variables:                       220
Nonlinear variables:                     0
Integer variables:                       0

Total constraints:                    4115
Nonlinear constraints:                   0

Total nonzeros:                       7986
Nonlinear nonzeros:                      0

                              Variable           Value        Reduced Cost
                              MTT( 1)         2.000000            0.000000
                              MTT( 2)         2.000000            0.000000
                              MTT( 3)         2.000000            0.000000
                              MTT( 4)         2.000000            0.000000
                              MTT( 5)         2.000000            0.000000
                              MTT( 6)         2.000000            0.000000
                              MTT( 7)         2.000000            0.000000
                              MTT( 8)         2.000000            0.000000
                              MTT( 9)         2.000000            0.000000
                             MTT( 10)         2.000000            0.000000
                             MTT( 11)         2.000000            0.000000
                             MTT( 12)         2.000000            0.000000
                             MTT( 13)         2.000000            0.000000
                             MTT( 14)         2.000000            0.000000
                             MTT( 15)         2.000000            0.000000
                             MTT( 16)         2.000000            0.000000
                             MTT( 17)         2.000000            0.000000
                             MTT( 18)         2.000000            0.000000
                             MTT( 19)         2.000000            0.000000
                             MTT( 20)         2.000000            0.000000
                             MTT( 21)         2.000000            0.000000
                             MTT( 22)         2.000000            0.000000
                               PT( 1)         3.000000            0.000000
                               PT( 2)         3.000000            0.000000
                               PT( 3)         3.000000            0.000000
                               PT( 4)         3.000000            0.000000
                               PT( 5)         3.000000            0.000000
                               PT( 6)         3.000000            0.000000
```

Figure 9. the shot of the results of Lingo Software after solving the single route case study based on the OPTIMAL INCREASE model (Process 3)

All trains of the Same Order approach departed based on the initial dispatch order, while trains of Order Free were allowed to stray from original patterns.

In the Same Order approach, all intermodal (dark blue) and freight trains (blue) departed after the first passenger train (yellow) with MDB equal to zero, although they could have departed earlier. The MDB parameter was assumed as zero for the passenger train; intermodal and freight trains were allowed to be departed 90 minutes earlier than the initial schedule without dependence on the train schedule. The duration of the timetable in the Order Free approach is shorter than the Same Order pattern (30 minutes), but the model also proposed more stops. The test confirmed that the OPTIMAL INCREASE model was able to automatically improve the initial timetable of Process 1 with 25 schedule conflicts and develop a Conflict Free schedule with both the Same Order and Order Free approaches.

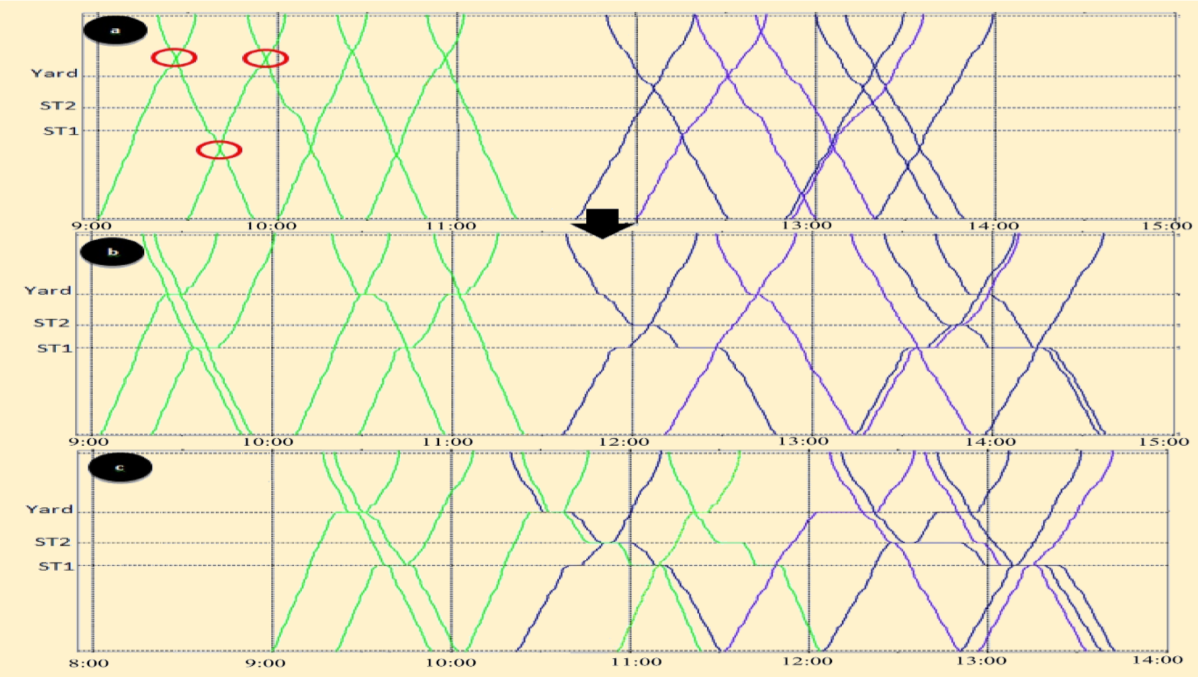


Figure 10. The initial timetable (a) with several schedule conflicts (three of them marked as an example), improved timetables after the OPTIMAL INCREASE optimization: Same-Order approach (b), Order-Free approach (c)

5.1.2. Process 2: Initial Timetable of OPEN RAILS with No Conflict

The goal of this process was to evaluate the capabilities of the OPTIMAL INCREASE model to compress an initial timetable with no schedule conflict (for example, long waiting time at some stations).

The initial timetable with serious conflicts (presented in Process 1, Figure 10 top) was simulated in OPEN RAILS to resolve the conflicts. OPEN RAILS can automatically resolve the conflicts of any requested timetable, but in some cases, the results of the simulated timetable are later manually improved by expert users. The same steps of developing the datasets and running the OPTIMAL INCREASE model were conducted for this process. Table 8 summarizes the user-defined parameters of the OPTIMAL INCREASE model used in Process 2.

Figure 11 presents the results of the initial timetable developed by OPEN RAILS (top) and the improved timetable by the OPTIMAL INCREASE model in the middle. The OPTIMAL INCREASE model could compress the timetable by almost one hour and improve the maximum dwell times (from 61 to 30 min) and total dwell times (from 271 to 168 min) of train trains.

To evaluate the station capacity limitations of the OPTIMAL INCREASE model, it was assumed that station “ST2” could receive only two trains simultaneously. In Figure 11 (middle), three trains either pass or stop at “ST2” around 9:30 am, which is more than the station's capacity. The capacity issue was fixed by departing the third train (train “A”) after train “B,” and modified input was used to rerun the OPTIMAL INCREASE model and update the timetable.

Table 8. Details of defined parameters for the OPTIMAL INCREASE model to solve Process 2 (OPEN RAILS timetable with no conflict)

Criteria	Passenger	Intermodal	Freight
Minimum allowed dwell time(minute)	0		
Maximum allowed dwell time(minute)	10	30	30

Criteria	Passenger	Intermodal	Freight
MDB(minute)	60	180	180
MDA(minute)	240	300	300
Headway(minute)	2		
Priority	3	2	1

Figure 11 (bottom) presents the second round of the OPTIMAL INCREASE model results with changes in the stop patterns of trains "A" and "C" highlighted. The capacity shortcoming at station "ST2" was fixed in the second round, while stop patterns and departure orders were kept for all other trains. The total duration of the timetable was increased by almost 20 minutes since trains "A," "C," and all trains after "C" departed 20 minutes later to address the station capacity shortcoming.

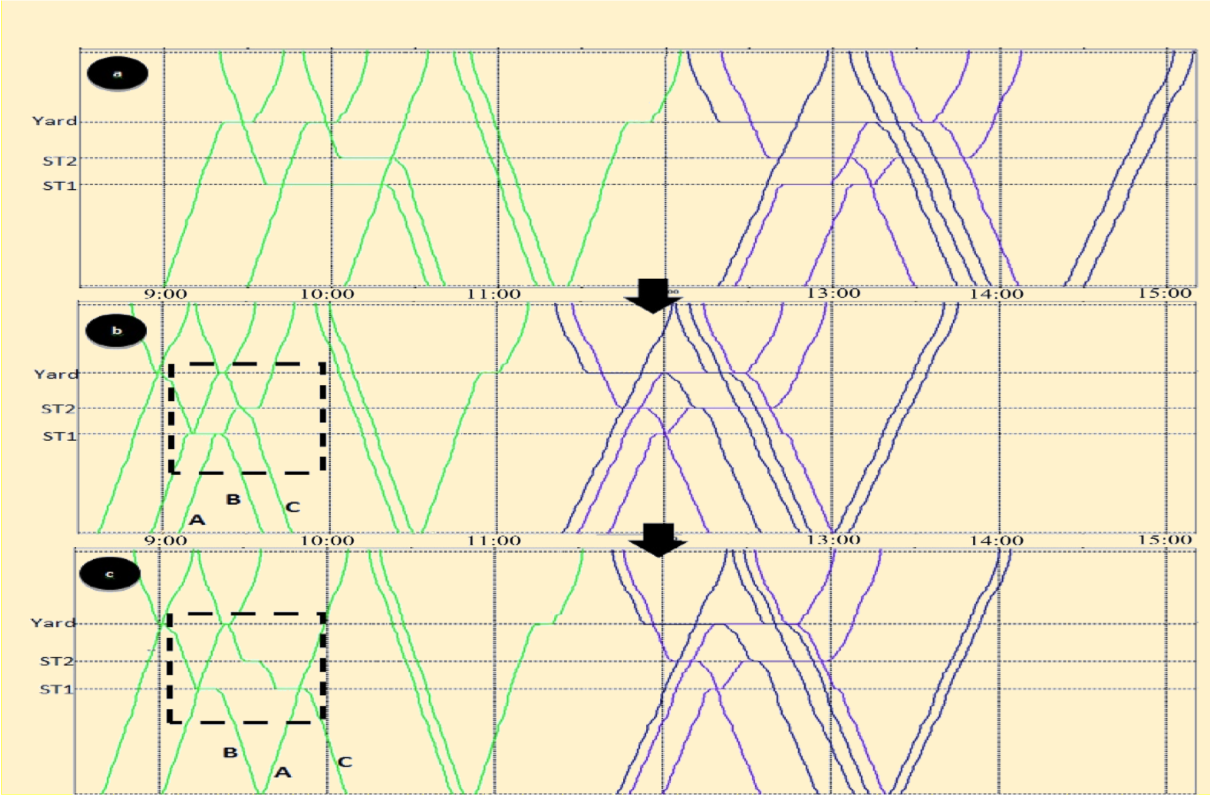


Figure 11. The initial timetable developed in OPEN RAILS with no manual improvement (a) was improved using the Same-Order approach of the OPTIMAL INCREASE model (b), and then it was readjusted by running the OPTIMAL INCREASE model for the second time to address the assumed station capacity limits in ST2 siding (c)

Table 9 compares the results after applying the optimal increase model. According to Table 9, the optimal increase model can reduce the total and maximum dwell times and reduce the timetable period, which means better capacity utilization.

Table 9. Comparison between initial and improved timetable developed by the OPTIMAL INCREASE model in Process 2 of single route case study (Same Order approach)

Criteria		Process 2	
		Initial timetable	Improved by Optimal Increase model
LOS	Number of stops	14	19
	Minimum dwell time	0	
	Maximum dwell time	61	30
	Total dwell time	271	166
Capacity	Timetable duration	6h10min	5h 25min

	Criteria	Process 2	
		Initial timetable	Improved by Optimal Increase model
	Timetable compression LEVEL	-	45min
			12%

5.1.3. Process 3: Comparing the Results of Open Rails and OPTIMAL INCREASE Compression Techniques

This process aimed to perform parallel timetable compression by the OPTIMAL INCREASE model and Open Rails and compare the results. The timetable compressed by both Open Rails and OPTIMAL INCREASE model was the initial conflict-free timetable presented in the previous process. This timetable was automatically improved by the UIC compaction technique of Open Rails, similar to the defined criteria (max dwell time: 10 minutes, overtaking allowed at the station).

The same exercise was repeated in the OPTIMAL INCREASE model, assuming the same max dwell time of 10 minutes. However, the compression technique structure for stop patterns and departure flexibility parameters differ in OPTIMAL INCREASE and Open Rails. Table10 summarizes the user-defined parameters of the OPTIMAL INCREASE model used in Process 3.

The initial timetable (Figure 12-a) and the improved timetable developed by Open Rails and the Same Order approach of the OPTIMAL INCREASE model (Figure 12-b and c) reveal the difference in train movement patterns between the improved timetables by OPTIMAL INCREASE and Open Rails.

Table 11 compares the results of Open Rails and OPTIMAL INCREASE improvements. OPTIMAL INCREASE model provided approximately 36 min' shorter timetable duration (better capacity utilization) than Open Rails, but the number of stops was slightly increased (11 vs. 9).

Table 10. Details of defined parameters for OPTIMAL INCREASE model to solve Process 3

Criteria	Passenger	Intermodal	Freight
Minimum allowed dwell time(minute)	0		
Maximum allowed dwell time(minute)	10		
MDB(minute)	180		
MDA(minute)	240	300	300
Headway(minute)	2		
Priority	3	2	1

Also, the results show that while both the OPTIMAL INCREASE model and Open Rails could significantly improve the Level of Service parameters in comparison to the initial timetable, the duration of timetabled developed by both compression models was slightly increased, mainly due to the sizable reduction in maximum dwell time from 61min to 10 min.

Table 11. Comparison between initial and improved timetable developed by Open Rails and OPTIMAL INCREASE model in Process 3 of single route case study (Same-Order approach)

	criteria	Process 3		
		Initial timetable	Improved by Open Rail	Improved by Optimal Increase model
LOS	Number of stops	14	9	11
	Minimum dwell time	0		
	Maximum dwell time	61	10	10
	Total dwell time	271	80	66
Capacity	Timetable duration	6h10min	7h 04min	6h 28min
	Timetable compression LEVEL	-	-	36
				8%

The research team also compared the compression techniques of Open Rails and the OPTIMAL INCREASE model by considering the output of the improved timetable by Open Rails (Figure 12-b) as the initial timetable of the OPTIMAL INCREASE model and by evaluating whether OPTIMAL INCREASE could further improve the timetable. OPTIMAL INCREASE used the same maximum 10 min' dwell time. After running the OPTIMAL INCREASE model, it was concluded that the results were almost identical to the initial timetable (Open Rails output) in all aspects of analysis, including the number of stops, stop pattern, total dwell times, and timetable duration.

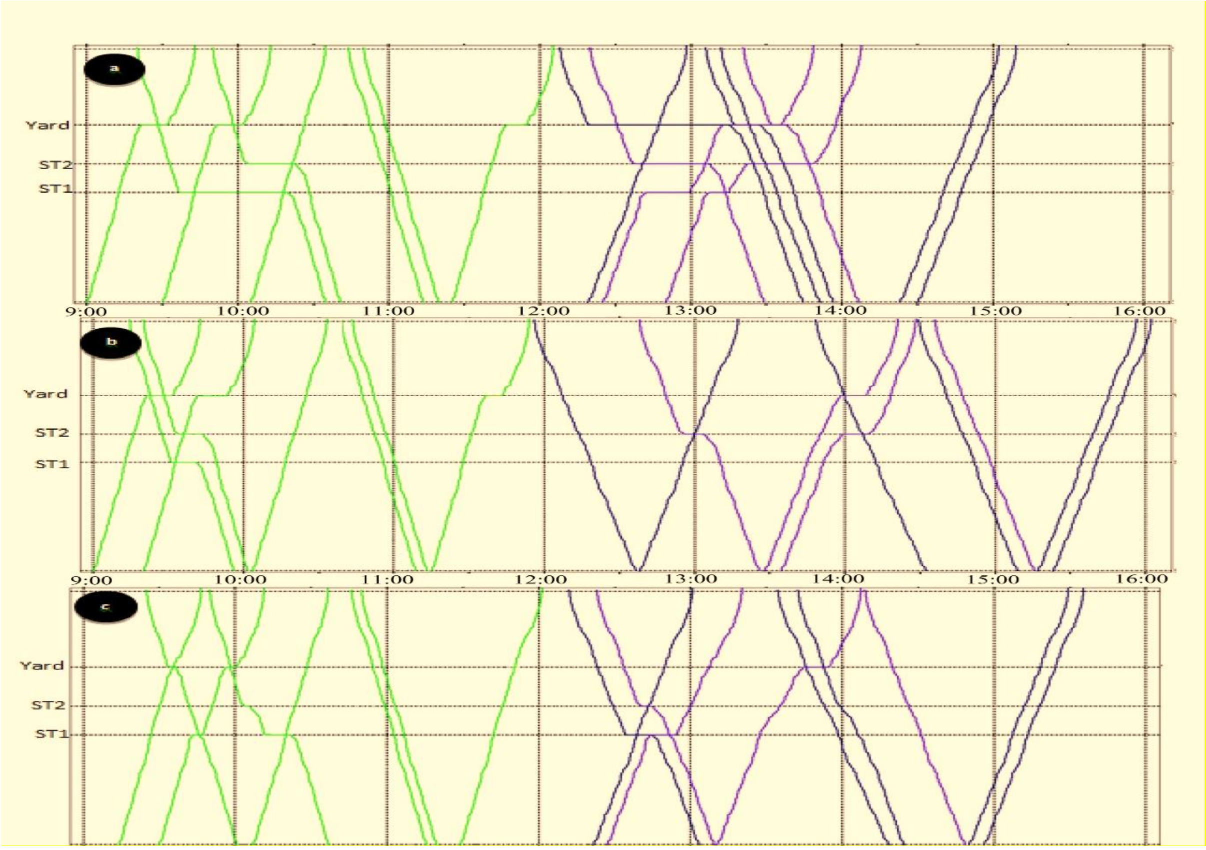


Figure 12. The initial timetable (a) was improved by Open Rails (b) in comparison to the output developed by OPTIMAL INCREASE model (c) with a shorter timetable duration

5.2. Generalities of the OPTIMAL INCREASE Model Results for Single Route Case Study

Several processes were successfully implemented in the OPTIMAL INCREASE model to test the hypotheses on a single route case study. Based on the test:

- Open Rails and OPTIMAL INCREASE models provide similar compression outcomes, even though the techniques are different.

5.3. Planning with Interference: Compaction of Timetable with Several Contrasts

We examined the optimal increase model performance in resolving conflicts and timetable compressing in an initial schedule (timetable) with several contrasts. A summary of the model parameters defined by the user for this plan is given in Table 12. Flexible parameters such as MDA and MDB were considered the same at all stations. The exit and stop schedules set by the LINGO were created in less than four seconds for both at the exact times (4114 constraints, 7984 non-zero parameters, 220 variables, 271).

Table 12. Optimal increase model parameters in a single-line plan (timetable with contrast)

parameter	Freight	Mixed	Passenger
Minimum stay time (min)	0		
Maximum allowed stay time (min)	60	20	10
MDB (min)	300	300	0
MDA (min)	240		
Advance (min)	2		
Train priority	1	2	3

The no order and solver repetition methods (4115 constraints, 7986 non-zero parameters, 220 282 solver iterations). In a similar approach, all passenger, freight, and intercity trains with zero MDB moved. In the no-order approach, the MDB parameter for passenger trains was set to “0”. In contrast, commuter, intercity, and freight trains were allowed to move 90 min earlier than the original schedule without dependence on the passenger train schedule.

The MDB values changes in the no-order approach led to a change in the order of some trains. For example, passenger trains started moving in the no-order approach after two passenger-freight trains (trains 1 and 2). The timetable in the no-order approach was approximately 30 min shorter than the same-order approach but with additional stops.

5.4. Sensitivity Analysis of Beta Coefficients

As mentioned earlier, there is a significant difference in the numerical values of the two variables, minimized by the objective function. The stop time deviation numerical value (the first part of the objective function) is much lower than the train movement time numerical value (the second part).

The coefficients parameters of ß1 and ß2 were included in the model to show the importance of stay time versus exit time, respectively, and to allow the user to set the weight preferences by changing these coefficients. In order to evaluate the weighting effect of ß1 and ß2 on the model results, a repeated sensitivity analysis was carried out for the first studied process, single-line (both approaches of the “same order” and “no order”). All values ß1 and ß2 were normalized between 0 and 1 (ß1+ß2=1) in the analysis, and seven different combinations were used to compare the main outputs of the optimal increase model (stops number, maximum stop time, total stop time, and timeline length).

A summary of the sensitivity analysis results is given in Tables 13 and 14. Changing coefficient values does not influence the maximum stop time obtained by the model (in all cases, 20 min), although it can be increased to a maximum of 60 min for freight trains.

Table 13. Sensitivity analysis between beta coefficients and the optimal increase model results, same order approach

ß1 & ß2	Number of stops	Maximum stop time	Total stop time	Length of the timetable period
0.0001,0.9999	26	20	227	337
0.9,0.1				
0.75,0.25				
0.5,0.5	26		216	337
0.25,0.75	24		161	336
0.1,0.9	24		155	334
0.0001,0.9999	22		144	338

The time in the timetable for the same-order approach (values between 334 and 338 min) had minimal changes, and this number remained constant (410 min) for the no-order approach. We assume that the initial timetable type (congestion level and train initial movement time), and the flexibility parameters for train movement, MDB means earlier and MDA means later, have a more substantial influence on the duration within the timetable and the maximum stop time than changing beta coefficients. On the other hand, Tables 13 and 14 show that the total stop time parameters and stops number are sensitive to changes in beta values.

The stops number and total residence time are insensitive (ß1<0.25 and ß2> 0.75) when ß1 is much lower than ß2. However, increasing the ß1value to above 0.25 gradually reduces the stop number and total stop time. Considering the time within the timetable and the maximum stop time were constant for almost all cases (Tables 13 and 14); therefore, the normalized value ß1 should be between 0.75 and 0.9 (ß2 between 0.1 and 0.25) in order to minimize the stops number and the total stop time in a single-line case study.

Table 14. Sensitivity analysis between beta coefficients and optimal increase model results, trains different order approach

ß1 & ß2	Number of stops	Maximum stop time	Total stop time	Length of the timetable period
0.0001,0.9999	22	20	223	410
0.9,0.1				
0.75,0.25				
0.5,0.5	21		200	
0.25,0.75	19		149	
0.1,0.9	20		141	
0.0001,0.9999	21		134	

6. Results

Rescheduling is one of the main techniques to improve the capacity utilization or features of the level of service in a rail corridor.

We can find no simulations of the railway with either (i) automatic trains interference resolution or (ii) automatic timetable management, and this is mainly observed for management tools of rail environment that use scheduling-based operating principles.

A new reprogramming model, "Optimal line capacity increase," is introduced in this paper to remove some of these limitations. The optimal increase model acts with railway scheduling tools and increases their capabilities for improving the utilization of capacity or service level parameters to provide a non-interfering and tight timetable for one or multi-line rail networks, such as one and multi-line corridors.

The optimization section of the optimal increase model receives several new rescheduling parameters from the timetable management tool, in addition to parameters defined by the user, such as minimum/maximum allowable stop time and parameters related to the flexibility and variability of train exit time.

The purpose and performance of the optimal increase model are adapted from the timetable compaction technique provided by the UIC. This plan tries to compress the train schedules as much as possible by minimizing the route time and deviating from the minimum time allowed for stopping with maintaining a plan without interference.

The optimal increase model generates two separate outputs, including the proposed exit time and the proposed stop time, that can be validated in the scheduling management tools. The optimal increase model can be used for rescheduling methods with the same order and no order of movement.

A single-line case study was applied to evaluate the optimal increase model capabilities. In the optimal increase model, we can compress the timetable, reduce the stop time, or save the initial timetable performance. Although the optimal increase model acted well, some limitations still need to be considered in future investigations.

The station capacity constraints can be eliminated by using the station capacity constraint variable. This makes the model more user-friendly and reaches the final solution with a one-time run. This can provide more capacity in the middle of the timetable and can be maximized through a two-objective algorithm for simultaneously minimizing the selected train's travel time.

7. Conclusions

Reschedule, and a specific type of rescheduling called "timetable compression," is one of the principal ways to improve the operational characteristics of a rail corridor.

While there are several timetable gadgets and rail simulation ways with operational management capabilities available in the rail industry, the features vary from tool to tool, and timetable management techniques or optimization models for rescheduling and timetable improvement are limited, specific in tools that target rail environment with more non-timetable based operating regulations.

A new standalone analytical model called “Optimal Increase” was introduced in this paper. OPTIMAL INCREASE can work in conjunction with any rail simulation software, and it can be rescheduling an initial timetable (with or without conflict) to provide a Conflict Free timetable. OPTIMAL INCREASE includes an optimal model which accepts some of the main rescheduling parameters from the simulation and timetable management tool results, in addition to user parameters. Optimal Increase results can be used to update the requested departure and dwell times for validation in the simulation software or to perform further analysis and computing based on the new optimized outcomes.

There are several applications in which the OPTIMAL INCREASE model can be used to improve the initial timetable, including:

1. Reschedule an initial timetable to provide a “Conflict Free” timetable based on a defined criterion
2. Analyzing different stop patterns, flexibility of trains to depart earlier or later, and min or max dwell times for selected trains to evaluate the LOS and capacity utilization under new process
3. Compressing the initial timetable to Provide more capacity ؛ shorter timetable duration of existing trains for additional trains
4. Reschedule trains by preserving the same order of initial departure times before improving the Same Order approach or by shuffling trains based on the new early departure times

The paper demonstrated and analyzed a case study with several processes to examine the different capabilities and hypotheses of the OPTIMAL INCREASE model (mentioned above).

In process 1, after running the model in LINGO, the adjusted departure and dwell times of the improved timetable were generated by LINGO for both Same Order and Order Free approaches, but in separate model runs. More than 25 initial timetable schedule conflicts were resolved in the Same Order and Order Free approaches by providing appropriate meet or pass stop patterns for train trains at the stations.

In process 2, The OPTIMAL INCREASE model could compress the timetable by almost one hour and improve maximum dwell times (from 61 to 30 min) and total dwell times (from 271 to 168 min) of trains at stations.

To evaluate the station capacity limitations of the OPTIMAL INCREASE model, it was assumed that station “ST2” could receive only two trains simultaneously. In Figure 11 (middle), three trains either pass or stop at “ST2” around 9:30 am, which is more than the capacity of the station. The capacity issue was fixed by departing the third train (train “A”) after train “B,” and modified input was used to rerun the OPTIMAL INCREASE model and update the timetable.

Figure 11 (bottom) presents the second round of the OPTIMAL INCREASE model results with changes in the stop patterns of trains “A” and “C” highlighted. The capacity shortcoming at station “ST2” was fixed in the second round, while stop patterns and departure orders were kept for all other trains. The total duration of the timetable was increased by almost 20 minutes since trains “A,” “C,” and all trains after “C” departed 20 minutes later to address the station capacity shortcoming.

In process 3, The initial timetable (Figure 12-a) and the results of the improved timetable developed by Open Rails and the Same Order approach of OPTIMAL INCREASE model (Figures 12-b and c) reveal the difference in train movement patterns between the improved timetables by OPTIMAL INCREASE and Open Rails.

The OPTIMAL INCREASE model provided approximately 36 min' shorter timetable duration (better capacity utilization) than Open Rails, but the number of stops was slightly increased.

Also, after process three, the results show that while both the OPTIMAL INCREASE model and Open Rails could significantly improve the Level of Service parameters in comparison to the initial timetable, the duration of timetabled developed by both compression models was slightly increased, mainly due to the sizable reduction in maximum dwell time from 61min to 10 min.

Similar to the results in the paper, the OPTIMAL INCREASE model could either improve the same criteria of an initial timetable as synopsis below:

- Resolving the scheduling conflicts of an initial timetable, in both Same Order and Order Free reschedule (Process 1)
- Compression of a merge timetable (Process 2)
- Comparison between the compression techniques of the OPTIMAL INCREASE model and Open Rails (Process 3).

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