Improvement of maintenance timetable stability based on event specific flexibility assignment in track choice PESP

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Improvement of maintenance timetable stability based on iteratively assigning event flexibility in FPESP

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Abstract
In the operational management of railway networks, an important requirement is the fast adaptation of timetable scenarios, in which operational disruptions or time windows with temporary unavailability of infrastructure, for instance during maintenance time windows, are taken into consideration. In those situations, easy and fast reconfiguration and recalculation of timetable data is of central importance. This local and temporal rescheduling results in shifted departure and arrival times and sometimes even in modified stop patterns at intermediate stations of train runs. In order to generate reliable timetabling results it is a prerequisite that train-track assignments, as well as operational and commercial dependencies are taken into consideration. In order to refer to the right level of detail for modelling track infrastructure and train dynamics in the computer aided planning process we present a generic model that we call Track-Choice FPESP (TCFPESP), as it implements suitable extensions of the established PESP-model. We show how the service intention (the timetable specification resulting from line planning) together with resource capacity information can be utilized in order to configure the TCFPESP model.
In addition, we are able to calculate quantitative performance measures for assessing timetable quality aspects. In order to achieve this we present a method for evaluating timetable robustness. By utilizing delay impact values resulting from max-plus algebraic performance analysis, we are thus able to iteratively distribute event flexibility in such a way that overall robustness of the maintenance timetable is improved.
This approach supports the planner to generate integrated periodic timetable solutions in iterative development cycles.

Keywords
Flexible PESP, Mesoscopic railway topology, Service Intention, Timetabling with track assignment, Timetable stability analysis

1 Introduction

1.1 Generating and investigating temporary timetable scenarios

In the operational management of railway networks, an important requirement is the fast adaptation of timetable scenarios, in which operational disruptions or time windows with temporary unavailability of infrastructure, as for instance during maintenance time windows (‘possessions’, see RailNetEurope 2017), have to be accounted for. In those situations, easy and fast reconfiguration and recalculation of timetable data is of central importance. This local and temporal rescheduling results in shifted departure and arrival times and sometimes even in modified stop patterns at intermediate stations of train runs. Only recently, van Aken et al. presented a PESP based macroscopic model for solving train timetable adjustment problems (TTAP) under infrastructure maintenance possessions (2017a). They show, that by applying TTAP, they are able to adjust a given timetable to a specified set of station track and complete open-track possessions by train retiming, reordering, short-turning and cancellation. In (2017b) they apply several network aggregation techniques to reduce the problem size and thus enable the model to solve large instances within short computation times with instances of the complete Dutch railway network.

However, in order to generate reliable timetabling results it is prerequisite that besides train-track assignments, also operational and commercial dependencies are taken into consideration. Hence, finding the right level of detail for modelling track infrastructure and train dynamics is crucial for supporting the planning process in an optimal way.

In day-to-day business, determining the feasible event times for individual train runs and the corresponding resource-allocation fitting into efficient transport chains resulting from an integrated clockface timetable is time-consuming and is carried out manually. On the other hand, algorithmic approaches for solving this task computationally require models based on microscopic information about track capacity. This capacity information is aggregated to (normative) minimum headway constraints that are used for solving standard periodic timetabling problems. In order to facilitate this step, several research groups made suggestions, how to combine common timetabling procedures with constraints resulting from mesoscopic infrastructure information. Hansen and Pachl (2008) show how running, dwell and headway times at critical route nodes and platform tracks must be taken into account for train processing and present a deep timetable quality analysis depending on these parameters. De Fabris et al. (2014) calculate arrival and departure times, platform and route assignments in stations and junctions that trains visit along their lines. Bešinović et al. (2016) present a micro–macro framework based on an integrated iterative approach for computing a microscopically conflict-free timetable that uses a macroscopic optimization model with a post-processing robustness evaluation. Caimi et al. (2011) extend PESP (see e.g. Serafini and Ukovich (1989) and Liebchen and Möhring (2007)) and propose the flexible periodic event scheduling problem (FPESP), where intervals are generated instead of fixed event times. By applying FPESP, the output does not define a final timetable but an input for finding a feasible timetable on a microscopic level, (Caimi (2009) and Caimi et al. (2009)).

1.2 Service Intention based approach for timetable specification

To improve customer value even under limited operating conditions, such as those encountered during infrastructure maintenance intervals, our modelling approach for creating temporary schedules is also based on an extension of PESP and takes the ‘service intention’ (SI) as input data. The SI was first described in Wüst et al. (2008), formally specified in Caimi (2009) and integrates commercial timetabling requirements given by the respective demand oriented ‘line concept’ on one side and technical constraints on the other. The ‘line concept’ results from a strategical planning process which is executed by the transport carrier. In this process, the available amount, the dynamics and the circulation of rolling stock are taken into account. In Switzerland, the integrated fixed-interval timetable (IFIT) is created on the basis of SI's. The required system times (minimum travel times between node stations, see for example Herrigel (2015) and BAV (2011)) are a prerequisite (see e.g. Liebchen and Möhring (2007)).

The maintenance interval planning step (denoted as IP in the sequel) is executed by the infrastructure manager. In this step, the functional requirements of the SI are brought together with this mesoscopic infrastructure data model of a given scenario. Altogether these data can be maintained in a standard timetable editor (see for instance SMA Viriato, 2018). In this way, the SI represents functional timetabling requirements including line data, line frequencies and separations as well as line transfers at specific stations. Hence, it contains explicit information about intended transport chains but is still flexible enough, to allow different ways of operational planning and resource allocation. Like de Fabris et al. (2014), we call this level of abstraction of the available resources 'mesoscopic topology'. We call our FPESP model that we apply to this mesoscopic topology 'Track-Choice FPESP' (TCFPESP).

In order to evaluate timetable robustness criteria we use a special algebraic approach that is commonly known as max-plus algebra. This approach has been elaborated in mathematical detail by Goverde (2007) who also demonstrates the benefits of this algebraic approach for timetable stability analysis in practical applications. We apply this method for evaluating the robustness of our resulting timetable and try to improve the timetable based on this performance evaluation in successive re-planning iterations. More specifically, we show how the max-plus-delay impact analysis can help to improve timetable stability by iteratively adjusting local flexibility constraints in the configuration of the TCFPESP model.

1.3 Structure of this article

This article is structured as follows: In chapter 2, we describe the methodology for achieving the research goals. In section 2.1 we summarize the FPESP model which implements the idea of periodic timetabling with event flexibility. Extending this FPESP to our proposed mesoscopic model we present in Section 2.2 our TCFPESP-model. For the iterative configuration of the event flexibility in the TCFPESP we make use of the delay impact vector that we obtain from max-plus analysis. This is shown in section 2.3. In section 2.4 we describe the TCFPESP heuristic for reducing the overall delay impact. In chapter 3 (Case Study 'Kerenzerberg') we present the results from applying the methods introduced in chapter 2 and the coordinated application in a real-world scenario from eastern Switzerland. Finally, in chapter 4 we conclude with a summary of the findings and an outlook on future work.

2 Methodology

2.1 Periodic Timetabling with Event Flexibility

The classical PESP tries to determine a periodic schedule on the macroscopic level (i.e. without using the tracks at an operation point) within a period T. Event $e \in E$ takes place at time $\pi_e \in [0, T)$. The schedule is periodic with time period T, hence each event is repeated periodically $\{\dots, \pi_e - T, \pi_e, \pi_e + T, \pi_e + 2T, \dots\}$.

The choices of the event times π_e depend on each other. The dependencies are described by arcs $a = (e, f)$ from a set A and modelled as constraints in the PESP. The constraints always concern the two events e and f and define the minimum and maximum periodic time difference l_a and u_a between them. These bounds are given as parameters in the PESP model. We therefore look for the event times π_e for every $e \in E$ that fulfill all constraints of the form

$$l_a \leq \pi_e - \pi_f + p_a T \leq u_a$$

for all $a = (e, f) \in A,$, where p_a is an integer variable that makes sure, that these constraints are met in a periodic sense.

In order to avoid tedious iterations between the process steps “microscopic capacity planning” and “mesoscopic capacity planning” in case of infeasibility of the micro-level problem, one can improve the chance of finding a feasible solution by enlarging the solution space in the micro-level. This approach has been described in detail in Caimi et al. (2011b). We also implement this event flexibility method by adding some flexibility for the events of the event and activity network (E, A) by introducing lower and upper bounds to the event times of the arrival and departure nodes in Figure 1b. The final choice of the event times in the range between the lower and upper bound shall be independent for each event such that each value of the end of an activity arc should be reachable from each time value at beginning of that activity arc (see Figure 1a).

We are not forced to add this flexibility to all the events, but we can select the nodes where we want to add it, for instance only nodes corresponding to events in a main station area with high traffic density, where it is more difficult to schedule trains on the microscopic level. In general, one can say, that this placement of flexibility is the timetable configuration feature, which has the highest level of influence on improving operational stability. This is where the information provided by the max-plus measures of delay impact (see section 2.3 et seq.) can be utilized in order to achieve timetable robustness. For more details regarding the FPESP method, we refer to the article of Caimi et al. (2011b).

a

b

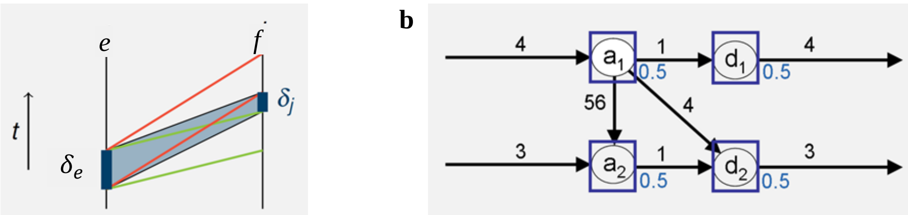


Figure 1: Target oriented placement of time reserves. a) Time frames $[\pi_e, \pi_e + \delta_e]$ in place of time points π_e. By implementing this method, the normal PESP constraints $l_a \leq \pi_e - \pi_f + p_a T \leq u_a$ now become $l_a + \delta_f \leq \pi_e - \pi_f + p_a T \leq u_a - \delta_e$ (see next section). In the example b) this means that instead of planning time points $(\pi_{a_1}, \pi_{d_1}, \pi_{a_2}, \pi_{d_2})$ we plan time frames $[\pi_e, \pi_e + 0.5]$ for $e \in \{a_1, d_1, a_2, d_2\}$.

2.2 Track-choice FPESP.

For our proposed timetabling model, we extend the FPESP method with events at track-level in order to generate event slot timetables on a mesoscopic level. In the TCFPESP model, the mesoscopic infrastructure consisting of sections is summarized as a set I of operation points. Operation points are largely tracks and stations but can also be other critical resources such as junctions (see OP ‘Tiefenwinkel’ in Figure 2b). As mentioned before, each operation point $i \in I$ is associated to a capacity consisting of a set of tracks T_i. A train run $l \in L$ is described by a sequence of operation points of I.

Based on this mesoscopic model we form an event-activity network (E, A). The set E

of events consists of an arrival event arr_{li} and a departure event dep_{li} for each train run $l \in L$ and operation point $i \in l$. The activities $a \in A$ are directed arcs from $E \times E$ and describe the dependencies between the events. For every train run we have arcs between arrival and departure events at the same operation points (dwell times or trip times) and arcs between departure and arrival events of successive operation points (running time between operation points). Further arcs include connections between train runs, headways and turnaround operations. Headway arcs $a \in A_H$ are especially important for explaining the 'track-choice FPESP model' below. Headways are used to model safety distances between trains running in the same and in opposite directions. For the sake of simplicity in the formal description of the TCFPESP we consider only headways related to one operation point, i.e. we omit headways for train runs in opposite directions over several successive operation points. The TCFPESP-model can be easily extended to include general headways.

We extended the classical PESP resp. FPESP model by using the number of tracks T_i at each operation point $i \in I$. The track-choice FPESP model assigns the arrival event arr_{li} and the departure event dep_{li} of train run l at operation point i uniquely to a track in T_i. We can use these assignments to switch on headway arcs $a \in A_H$ by using the following big-M-approach. In addition to variables π and p from the classical PESP model we need: (i) Binary variables tc_{et} (track choice) for each event $e \in E$ and track $t \in T_{i(e)}$, where operation point $i(e)$ is associated to event e, i.e. e is equal to arr_{li} or dep_{li} for a train run l. (ii) Binary variables h_a for every headway edge $a = (e, f) \in A_H$. As mentioned before, headway edges are always between events at the same operation point, therefore $T_{i(e)} = T_{i(f)}$ holds. (iii) Positive variables δ_e for each event $e \in E$ to model the event flexibility.

The track-choice model is defined by:

$$\min f(\pi, \delta)$$

$$s.t. \quad l_a + \delta_f \leq \pi_e - \pi_f + p_a T \leq u_a - \delta_e, \qquad \forall\ a = (e, f) \in A \setminus A_H, \tag{1}$$

$$l_a + \delta_f - (1 - h_a)M \leq \pi_e - \pi_f + p_a T \leq u_a - \delta_e + (1 - h_a)M, \qquad \forall\ a = (e, f) \in A_H, \tag{2}$$

$$\sum_{t \in T_{i(e)}} tc_{et} = 1, \qquad \forall\ e \in E, \tag{3}$$

$$tc_{arr_{li}t} = tc_{dep_{li}t}, \qquad \forall\ l \in L, i \in l,\ t \in T_i, \tag{4}$$

$$h_a \geq tc_{et} + tc_{ft} - 1, \qquad \forall\ a = (e, f) \in A_H,\ t \in T_{i(e)} \tag{5}$$

$$tc_{et}, h_a \in \{0,1\}, \pi_e \in [0, T), p_a \in \mathbb{Z}, \delta_e \geq 0, \qquad \forall\ e \in E, t \in T_{i(e)}, a \in A,$$

where M is a big enough natural number.

In (1) the normal FPESP constraints are summarized (without headway arcs). In (2) are the headway constraints, which can be switched off with a big-M technique. The assignment of the events to the tracks is done in (3). (4) is used to assign the corresponding arrival and departure events to the same track. In (5) the headway variable is set to 1, if the events take place on the same track, i.e. the headway is required at this operation point.

There are many different objective functions $f(\pi, \delta)$ suggested by Caimi et al. (2011b) for the FPESP model. To generate the traffic plan for our test scenario we use iteratively the TCFPESP with different objective functions (see Wüst et al (2018b)), namely:

- We minimize all passenger relevant times (i.e. $t \in A_T$ the set of trip arcs, $d \in A_D$ the set of dwell arcs and $c \in A_C$ the set of connections times). The weights w_t, w_d and w_c can be used for prioritizing certain times, e.g. connection times. We will call the model in this case MINTRAVEL, according to Caimi et al. (2011b). The objective function is defined as follows:

$$\min f_{TT}(\pi) = \sum_{t \in A_T} w_t \pi_t + \sum_{d \in A_D} w_d \pi_d + \sum_{c \in A_C} w_c \pi_c \tag{6}$$

- We maximize the flexibility in a certain range at certain arrival and departure events. The objective function is defined as follows:

$$\max f_{flex}(\delta) = \sum_{e \in V} w_e \, \delta_e, \tag{7}$$

  where $V \subseteq E$ is the set of all events where flexibility is introduced.
  Furthermore we add two constraints. The passenger travel time has to be smaller than $(1+\epsilon)$ times the best possible travel time from the model MINTRAVEL. The flexibility for all events is bounded by a maximal flexibility δ_{max} for a better distribution of the flexibility to all events. The two constraints are given by

$$f_{TT}(\pi) \leq (1+\epsilon) f_{TT}^{*} \quad \text{and} \quad \delta_e \leq \delta_{\max} \; \forall \; e \in E, \tag{8}$$

  where f_{TT}^{*} is the optimal value found for f_{TT} in (6).
  We will call the model in this case CONTRAVEL according to Caimi et al. (2011b). ϵ is a parameter controlling the quality of the schedule for the passengers' travel times and w_e will be used for individual adjustments in event flexibility in order to maximize timetable robustness (see section 2.3 and 2.4).

By using the models MINTRAVEL and CONTRAVEL iteratively we can generate a traffic plan covering stability and travelling time aspects (see Wüst et al (2018b)).

2.3 Computation of the Cumulative Delay Impact

The Cumulative Delay Impact (CDI) is a measure to quantify the overall impact that a certain delay κ at a specific event f has on all other events e. Formally the CDI is computed as follows:

$$CDI_f(\mathrm{R}) = \sum_{e \in E \setminus f} \max\left(\kappa - r_{ef}, 0\right)^{\gamma}, \tag{9}$$

where E denotes the set of all events. R represents the recovery matrix of size $|\, E \,| \times |\, E \,|$, where r_{ef} represents the actual buffer time between events f and e (see Goverde (2005) and (2007) for details) given a periodic timetable π. κ is the parameter that denotes the initial delay (in minutes) applied to node f, for which CDI_f shall be calculated. Finally $\gamma \geq 1$ is a parameter to increase the impact of positive differences between the delay κ and r_{ef}. In this study γ was always set to 1. Furthermore, CDI_f is strictly monotonically increasing in κ and $CDI_f(\mathrm{R}) = 0$ for $\kappa = 0, \gamma \geq 1$. The initial delay κ can of course be set for each event $f \in E$ individually. E.g. when κ is determined with the help of a statistical delay analysis for each event $f \in E$.

2.4 Heuristic for improvement of delay impact

We measure the robustness of a periodic timetable π by the sum of all cumulative delay impacts, i.e. we consider $f_{rob}(\pi) = \sum_{f \in E} CDI_f(\mathrm{R})$. Given an acceptable κ (from an operational point of view), we would like to have this measure as small as possible. From the definition of CDI it follows, that $f_{rob}(\pi)$ is bounded from below by 0.

It would therefore be natural to use $f_{rob}(\pi)$ in the CONTRAVEL model as objective function. Since we don't have a direct solution approach for this case, we propose the following heuristic.

Iteratively we try to use the weights w_f in the function $f_{flex}(\delta)$ to give more flexibility to the events $f \in E$, where $CDI_f(\mathrm{R})$ is not zero. We will use the following formula to compute w_f:

$$w_f = \left(\frac{CDI_f(\mathrm{R})}{\max_{\mathrm{f \in E}} CDI_f}\right)^{\alpha}, \text{ if } \max_{\mathrm{f \in E}} CDI_f > 0 \text{ and } CDI_f(\mathrm{R}) \geq \sigma;\ w_f = 0 \text{ otherwise} \qquad (10)$$

where $\alpha \geq 1$ is a parameter to increase the impact of relatively large $CDI_f(\mathrm{R})$ and σ is a threshold value, which is set to $\sigma = 0.4$ in Figure 5a and to $\sigma = 0$ in Figure 5b in the two improvement scenarios in section 3.4.

Iteration scheme: Improving delay impact

Input:

- Periodic timetable π computed with the CONTRAVEL model.
- Initial delay κ and parameter γ.

Iteration steps:

1. Compute $CDI_f(\mathrm{R})$ for all $f \in E$ and $f_{rob}(\pi)$.
   If $f_{rob}(\pi) = 0$, **stop and accept timetable $\boldsymbol{\pi}$.**
2. For timetable π set the weights w_f according to (10).
3. Recompute a new timetable π_{new} with the help of the CONTRAVEL model.
4. Compute $f_{rob}(\pi_{new})$ for the new timetable π_{new}.
   If $f_{rob}(\pi_{new}) = 0$, **stop and accept timetable $\boldsymbol{\pi_{new}}$.**
5. If $f_{rob}(\pi_{new})$ is smaller than $f_{rob}(\pi)$, set $\pi = \pi_{new}$ and go to step 2.
   If $f_{rob}(\pi_{new})$ is bigger or equal than $f_{rob}(\pi)$, **stop and accept timetable $\boldsymbol{\pi}$.**

All timetables during the iterations fulfil the same service intention (see section 1.2), but the resulting timetable is the most robust one with respect to the cumulative delay impact measure (among the constructed timetables during iterations). We illustrate this iteration scheme in our case study in section 3.

3 Case study 'Kerenzerberg'

In order to illustrate the iterative improvement of timetable stability for IP scenarios, we selected a railway corridor in the eastern part of Switzerland. We call the case study 'Kerenzerberg' and the maintenance work is planned on the network section between Flums and Mels. The impact on the schedule is that there is a reduced velocity on that section during normal operation hours.

3.1 Network segmentation

In order to avoid putting too much effort into entering information that is not needed and rather focus on the relevant perimeter for the IP timetabling scenario, one has to identify which part of the entire railway network has to be investigated and which part will be assumed to remain as given by the ordinary timetable. In a first step, the relevant lines and services operating on the subnetwork, which will be affected by the construction sites, have to be identified. In a second step, those lines, which are coupled (e.g. by transfers or technical dependencies) to these affected lines have to be found.

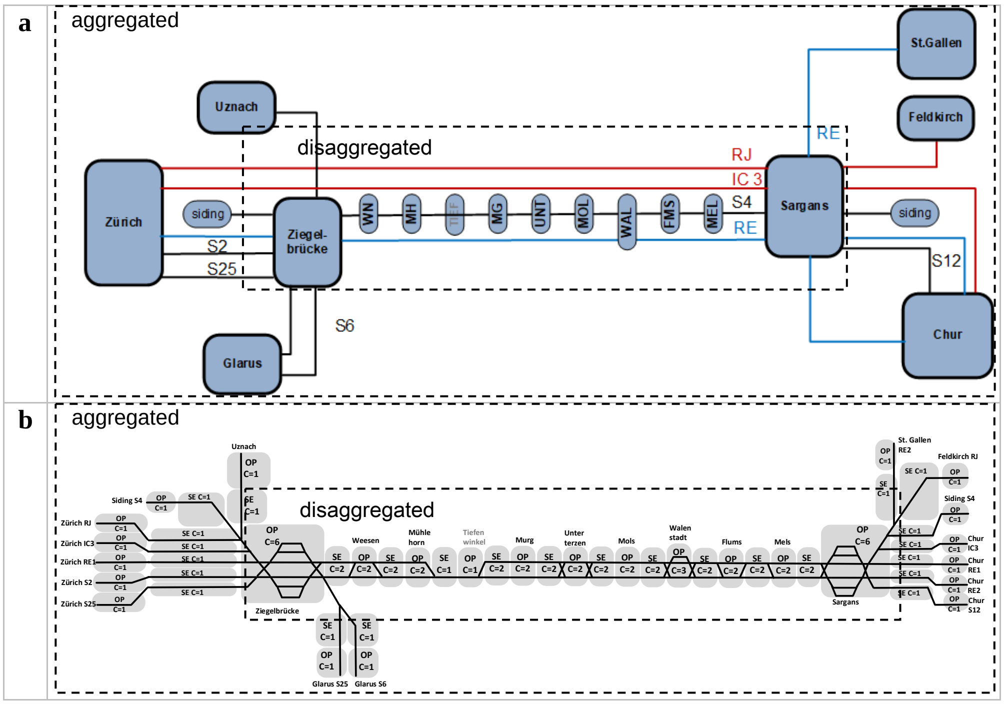


Figure 2: Case study Kerenzerberg a) In order to divide the relevant infrastructure for the IP timetabling scenario into a network partition with the relevant level of detail and a peripheral part with more coarse information, the railway network is divided into subnetworks. A disaggregated subnetwork containing the relevant infrastructure segments at mesoscopic level and an aggregated subnetwork, representing infrastructure on the macroscopic level. b) Shows the track topology for the both, the aggregated and disaggregated network partitions. The grey shaded topology points are indicated with it's type (operation point 'OP', or section point 'SE') and it's number of tracks (track capacity 'C'). In order to avoid treating line interactions outside the disaggregated partition, each line has an individual peripheral OP and the section between the final destination OP and the boundary OP that separates the two partitions from each other is configured with aggregated running times and dwell times of the respective line.

One has to identify the sub-network nodes which isolate the relevant infrastructure partitions from the fixed periphery. In this way one obtains a disaggregated subnetwork containing the relevant infrastructure segments and an aggregated subnetwork, representing infrastructure on the macroscopic level (see outer dashed square areas in

Figure 2 a and b). The disaggregated subnetwork is configured with all mesoscopic details. On this disaggregated subnetwork all train movements are planned in detail. For each line coming from or going beyond the boundary nodes of the disaggregated subnetwork we create a virtual end station node which is connected by a single section to the corresponding boundary node. The section lengths with the appropriate trip times, the turnaround times of the line outside the disaggregated subnetwork together with the run- and dwell times within the disaggregated subnetwork have to sum up to the proper roundtrip time. The mesoscopic track topology of the disaggregated subnetwork is illustrated in Figure 2 b).

3.2 Network of the case study Kerenzerberg.

The planned construction or maintenance work for our test scenario 'Kerenzerberg' is located on the network section between Flums and Mels. During the IP interval, trains are running with reduced speed in both directions. We decided to use the corridor Ziegelbrücke-Sargans as the disaggregated partition of the test network. It has to be mentioned, that there is a single track section between the operation points 'Mühlehorn' and 'Tiefenwinkel'. For this disaggregated network partition we iteratively generate IP timetable scenarios (see section 3.4). The western part of Ziegelbrücke is aggregated, i.e. we introduced the nodes Uznach, Zürich, Glarus and a siding of Ziegelbrücke and connecting tracks. The aggregated network will be used to maintain vehicle circulation (e.g. turnarounds) aspects of lines and to model connections to peripheric lines (see the description of SI in section 3.3). The eastern part of Sargans also belongs to the aggregated partition. We introduced the nodes St.Gallen, Feldkirch, Chur and a siding of Sargans. In the aggregated network we assume to have enough track capacity to compensate for delays.

3.3 Description of Service Intention

The configuration of the SI is mainly done in the planning system Viriato. Additional information like upper boundaries of time intervals and flexibility of event times as required in the TCFPESP model is maintained in an R-based table editor (see chapter 2.2). The SI-lines represent the lines in the corresponding timetable 2018 with minor adaptations. In order to demonstrate the turnaround operations within our test scenario, we decided that the line S4 makes a turnaround in a siding next to Ziegelbrücke and Sargans, respectively. Minimal line rotation times and line frequencies are indicated in Table 1.

Table 1: Line rotations and line frequencies

Line ID	Min. Line rotation time (modulo 60, min)	Line frequency (repetition / hour)
S4	56.6	1
RJ	45.8	0.5
IC 3	43.8	1
RE 1	52.8	1
S12	9	1
S25	14	1
S6	14	1
RE 2	14	1
S 2	9	1

Table 1: Line rotations and frequencies. The minimum line rotation times are computed according to the approach of Liebchen and Möhring (2007). The corresponding turnaround intervals are computed in such a way, that a service with a minimal number of rolling stock is possible. In our case study the line S4 is operating with one rolling stock. The other lines operate with more than one rolling stock due to longer round-trip times. These bounds are not computed according to Liebchen and Möhring (2007), they are set manually.

Ziegelbrücke and Sargans are considered as local hubs. At these stations the traffic plan has to account for passenger transfers between lines. Technically, these transfer requirements result in connections constraints in our TCFPESP-model. These line connections are indicated in Table 2. For a detailed definition of the infrastructure and the SI specification including time intervals of running times, dwell times, turnaround times, separation times etc. see Wüst et al. (2018b).

Table 2: Line Connections at Stations

Connection [1, 15] From/To at station	S 25 (ZB-GL)	S 25 (GL-ZB)	S 4 (ZGB-SA)	S 4 (SA-ZGB)	S 12 (SA-CH)	RE 2 (CH-SG)	IC 3 (ZGB-SA)	RE 1 (SA-ZGB)	RE 1 (ZGB-SA)	S 6 (GL-UZ)	S 6 (UZ-GL)
S 4 (ZGB-SA)	ZGB	ZGB			SA						
S 4 (SA-ZGB)		ZGB			SA						
S 25 (GL-ZB)			ZGB								
S 25 (ZB-GL)				ZGB							
IC 3 (ZGB-SA)						SA					
S 12 (CH-SA)							SA				
RE 2 (CH-SG)								SA			
RE 2 (SG-CH)							SA	SA			
RE 1 (ZGB-SA)											ZGB
RE 1 (SA-ZGB)										ZGB	ZGB
S 6 (GL-UZ)								ZBG	ZGB		
S 6 (UZ-GL)								ZGB			

Table 2: Case study Kerenzerberg: Line connections at stations are dependent on the direction of the train runs. The time intervals for connection arcs [lb, ub] is configured identically for all connections: [1 min, 15 min].

3.4 Iterative improvement of timetable robustness

Once the configuration of the SI and the mesoscopic infrastructure is complete it is transformed into the TCFPESP model which was implemented in GAMS by applying the the CONTRAVEL model as indicated by equations (7) and (8) with parameter $\epsilon = 0.5$. In case the SI is feasible with respect to the capacity constraints given by the infrastructure, GAMS returns the timetable π_{it_1} with capacity bands. These are plotted as time-distance diagram as shown in Figure 3. This represents the result of the first iteration it_1 of the timetable event flexibility adjustment. As can be seen in the diagram, the capacity time bands of the train runs are quite narrow which is due to a small $\delta_{max} = 10s,$ but show variable width within a certain range up to 10 seconds. They are quite homogenously

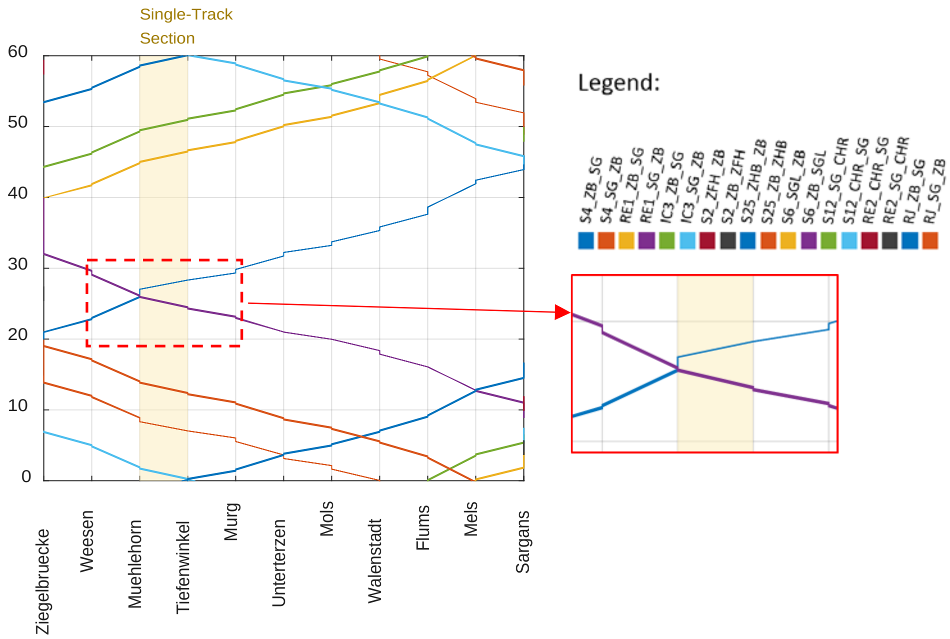


Figure 3: Time-distance diagram: GAMS output for TCFPESP applying the iteration scheme of section 2.4. Line names and directions are indicated by colours as shown in the legend. One can also see the narrow but variable width of the capacity time bands indicating a low flexibility of each train run in a range below one minute.

distributed, indicating some, but low flexibility in all timetable events. The robustness of this result is assessed by calculating the CDI_f(R) for an initial delay κ of 3 minutes. Figure 4a shows the delay impact of each timetable event to all other network events indicated by the corresponding colour (dark colours indicate higher delay impacts) together with the inter dependencies (connecting arrows) in the event activity network. In order to demonstrate the influence a target oriented adjustment of the event flexibility we selected all delay impacts above a threshold of $\sigma = 0.4$ and used them to calculate new weights w_f for the next iteration for calculating a more robust timetable π_{it_2} (see equation (10) and iteration scheme in section 2.4). This time the parameter δ_{max} is set to 60s in order to assign more flexibility to the critical events. The selected weights are shown at the right in Figure 4 for nodes with numbers above 150. Here node numbers are sorted with higher node numbers for high delay impacts. The time-distance diagram of the resulting timetable $\pi_{it_2}$with $\sigma = 0.4$ is shown in Figure 5a. One can clearly see that here certain timetable events have much more flexibility than others. If we sum up the delay impacts of all events in this scenario, we obtain a $f_{rob}(\pi)$ −value reduced to 87.0% compared to the one of π_{it_1} (see Figure 5d, result 'with few weights').

Figure 5b shows the time-distance diagram for the result of timetable iteration $\pi_{it_2}$with $\sigma = 0$. This means that in this iteration we selected all weights. In this scenario, the effect on the cumulative delay impact is even stronger. The resulting $f_{rob}(\pi)$ −value is reduced to 79.3% compared to the one of π_{it_1} (see Figure 5d, result 'with all weights').

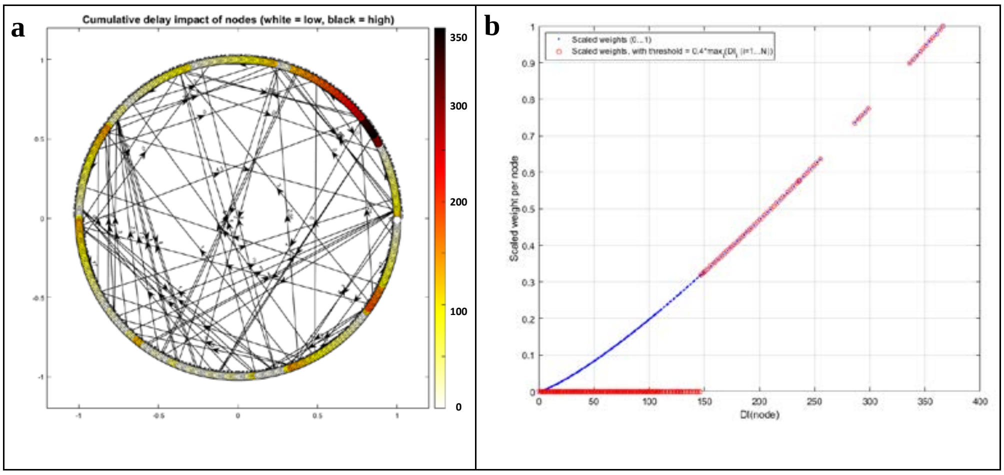
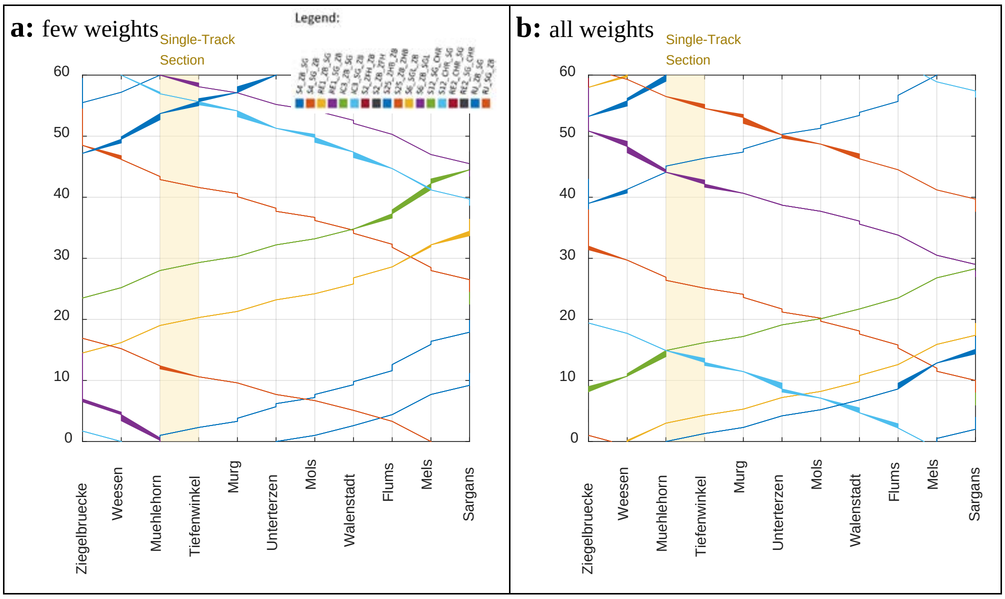
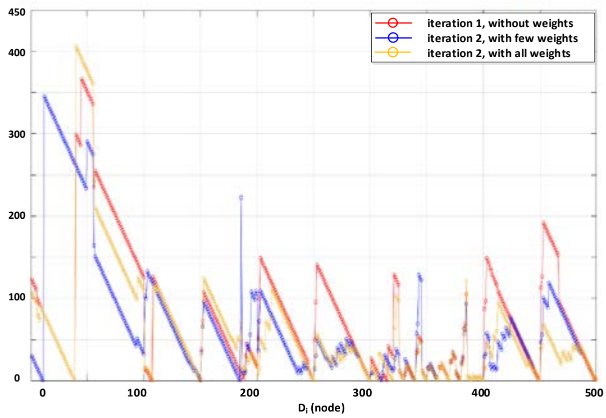


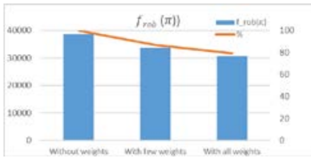
Figure 4: a) The values of the $CDI_f(R)$ for all event nodes indicated by a colour code ranging from 0 to 350 seconds and the interdependencies between the event nodes. b) shows the weights (calculated according to (10)) scaled to values in the range [0…1] for all event nodes sorted from left (low values) to right (high values). One can see that some event nodes (all events of the Railjet RJ) do not have any delay impact, as they do not have influence on other events.



c



d



$f_{rob}(\pi)$ for iterations with

- no weights (100%),
- with few weights (87%) and
- with all weights (79.3%)

Figure 5: a) and b) show time-distance diagrams for the second iteration of the timetable calculation π_{it_2} with a selection of weights w_f (a: σ = 0.4) and with all weights (b: σ = 0). Line colours are the same as in Figure 3. C) shows the distribution of the delay impact values across the event nodes f for timetable iteration it_1 with no weights applied (red curve), and for timetable iteration it_2 with few selected weigths (blue curve, see text for selection criteria) and for timetable iteration it_2 with all weigths applied (orange curve). d) indicates the improvement of iteration it_2 with respect to the iteration it_1 for both weighting scenarios.

4 Conclusions

The aim of this research was to show, that using the service intention as the demand oriented functional requirement for timetable generation one can generate timetable scenarios for maintenance interval planning in a fast and easy way. An additional requirement for generating reliable timetable scenarios is the usage of a mesoscopic infrastructure model for input to FPESP. Temporary changes of infrastructure properties like the number or the maximum allowed speed of tracks and switches reduce the available capacity for track assignments to train runs. For this reason, we introduce an extension of the FPESP model that we call ‘TCFPESP’ model. The TCFPESP model allows to make a target oriented adjustment of event flexibility by applying weights to the TCFPESP objective function. We obtain those weights from the calculation of the cumulative delay impacts for all timetable events and use them in an iterative manner for improving timetable stability.
We show results for a few scenarios which demonstrate that we can reduce the overall delay impact of timetable events by a significant amount (a reduction of more than 20% in the second iteration compared to the first iteration). We consider these preliminary results as promising for making target oriented improvements of timetable robustness, especially in cases where variability of process times is high and cannot be reduced by operational measures. Timetable events that have a strong influence on many other timetable events should be planned with more flexibility than those with low cumulated impact. In a next step we want to further investigate this observation with the help of simulations on microscopic level.

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