

# Generation of the transport service offer with application to timetable planning considering constraints due to maintenance work

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## Abstract

Line planning is an important step in strategic timetable planning in public transport. In this step the transport offer for the customer is generated by the public transport operator, whereby the resulting costs for the operator should be as deep as possible. Mathematical models for line planning allow to create optimized line plans quickly. Planners can use these models to rate and select different alternatives. This is particularly valuable under the aspect of increasing maintenance and construction tasks of the railway infrastructure. We show, that in this case, it is possible to create functional requirements for automated timetable creation from the result of line planning step. The practical use of the involved models is illustrated by a real application example.

**Keywords:** Timetable planning, Maintenance intervals, Transport service intention, Constraint relaxation, Line planning

## 1 Introduction

### 1.1 Generation of the transport service intention

Automation and digitization in the development of transport chains is a big challenge for public transport in the future. The goal is to achieve optimal and consistent planning across all process steps and time horizons to increase the degree of automation and service quality. The two major steps in transport service planning are (a) line planning and (b) timetable generation. These steps are carried out in several iteration loops involving co-

ordinated activities across different companies, such as railway operators and infrastructure managers. In both steps, mathematical models can support planning decisions. A detailed overview of mathematical models for step (a) line generation was provided by Schöbel (2012). Models considering both steps (a) and (b) are described in several publications (see, e.g. Barber et al. (2008) and Liebchen and Möhring (2007)). However, there is still little literature on the coordination of these models for practical applications (see Schöbel (2017)). This article is about the generation of timetable scenarios based on origin-destination (OD) demand-matrices and the transport service offer in public transport serving the OD-demand. We call this offer service intention (SI). The SI is represented by a set of public transport lines, including technical and commercial parameters. Technical line properties are represented by line categories and trip times. Commercial properties include dwell and transfer times and thus represent customer relevant service levels for each network OD-relation. A formal description of the SI was first presented by Caimi (2009). Caimi also demonstrated that the SI is an input suitable for the timetabling step (b) especially if the result of (b) is used as input for generating track slots for the configuration of a traffic management system at a microscopic level (see Caimi (2009)). Like the approach of Caimi et al. (2011), we make use of a timetabling model which is based on an extension of the PESP model. Our model refers to a mesoscopic level of infrastructure detail. We call this PESP extension TCFPESP (Track Choice Flexible Periodic Event Scheduling Problem) (see Wüst et al. (2018) and (2019) for technical details). In this article, we want to demonstrate that the SI can be generated automatically in step (a). To emphasize the relevance of our results, we demonstrate how the proposed method can be used as input for automatically generating the timetable considering constraints due to maintenance work in a real-world scenario.

## 1.2 Steps of the planning process

The method for step (a), which is presented here consists of the determination of line routes together with their frequencies in a specific rail network such that a given passenger transport demand can be satisfied. Lines typically connect two endpoints by a sequence of intermediary stations. All lines in a given rail network are hierarchically organized by line categories. Passenger demand for each line category is estimated based on a passenger assignment method, which is described in detail by Oltrogge (1994). We will refer to it as ‘system split’. Each line category has a maximum passenger capacity  $Cap$  which is determined by the seating capacity of the specific rolling stock unit of the line. The capacity of a line is then calculated from  $Cap$  and the operating frequency. If several lines are operated on the same track edge, the respective edge capacity in terms of a maximum number of train slots (e.g. per hour) has to be respected additionally. There are two conflicting objectives in line planning. On the one hand, the operating costs and on the

other a weighted combination of passenger travel times and the number of transfers is to be minimized. We will show, that the result of (a) is the SI. Once the SI is given, we create a timetable in (b) which can be tested for feasibility at a mesoscopic level of detail (see Wüst et al. (2019)). This timetable in combination with passenger flow is the basis for customer information as well as the subsequent steps of operational planning.

If there is a reduction in transport capacity, for instance, due to track maintenance work, it may happen, that no feasible timetable can be created which satisfies the SI. In this case, we propose to go back to the line planning step and create a new (relaxed) SI. The challenge is to find a feasible timetable which on one side has a low impact on the passenger service level in terms of total travel time and on the other side takes temporary reduced resource availability and operational restrictions into account. The innovation here is the fact, that the use of the SI allows going back to the previous planning step, i.e. the line planning step, in order to create a revised timetable input that takes into account the new restrictions.

### 1.3 Structure of this article

In chapter 2, we first describe a suitable line planning model that we selected for the application in maintenance timetable planning (see section 2.1). In section 2.2, we describe how the line plan is used to configure the SI, and in section 2.3, we describe how the SI is constructed, based on the results from the line planning step. The aim is to provide sufficient detail in order to be used for configuring the timetabling model TCFPESP. Finally, in chapter 3, we present the results of a case study, where we applied the methods described in chapter 2 to a real-world scenario. We apply the methods for generating an (adapted) transport service offer and applying it to timetable planning twice, once for generating a reference timetable for a given network scenario and once considering constraints due to maintenance work on a section in the given network. In chapter 4, we summarize the findings of our proposed approach and make some conclusion that we also use to motivate future research for further elaborating the iterative planning process.

## 2 From line planning to timetabling

In this section, we give a short description of the proposed line planning (section 2.1) and the timetabling model (section 2.3). The generation of SI (section 2.2) is the main contribution of this paper.

## 2.1 Generating the line plan in planning step (a)

The customer demand in the line planning step (a) is given by an OD-matrix, in which the coefficients represent the demand between pairs of nodes in a given period  $T$  (e.g. 60 minutes). The basic requirement is to cover the demand for transportation according to the OD-matrix, the customer-friendliness is based on the shortest possible journey times and the cost-efficiency is given by achieving these goals at the lowest possible operating costs.

The line planning model presented here builds on the solution approach of Friedrich et al. (2017). They describe in detail how lines and the appropriate line frequencies from a given line pool are selected. In the strategic planning process, a line pool represents all lines belonging to a given line category, such as intercity lines or commuter train lines. Each line  $l$  in the line pool  $\mathcal{L}_0$  is specified by its route  $(v_0^l, \dots, v_K^l)$ , i.e. its sequence of station or stop locations  $v_k^l$ ,  $k = 0, \dots, K$ , out of the set of stations  $N$ , its vehicle type, its trip times from stop to stop and an OD demand for the corresponding line category.

The application in chapter 3 refers to tactical planning requirements as we want to determine a timetable, which takes time intervals with reduced track capacity into consideration. There, we assume the set of given line pools (for the different line categories) to be fixed in the case of normal operations. For the time interval with maintenance work, we will adapt the line pool due to reduced track capacity (see section 3.4). We show, how the frequencies of different lines in the line pool and the corresponding timetable can be derived from the underlying OD-demand once for the case of normal operations and once for the case of the maintenance work on a certain track segment. The line planning model is based on two different network types, the ‘Public Transport Network’ (PTN) and the ‘Change & Go Network’ (CGN) (see Schöbel, 2012 for an introduction). The PTN is an undirected graph with station nodes  $v \in N$  connected by direct track edges  $e \in E$ . In the PTN only existing track connections are considered.

As there are three line categories given in our application example we also have three categories of station or stop locations: intercity (IC), interregio (IR) and commuter (S-Bahn, see Table 1). This follows from the system split, which is described in section 1.2. Hence, every node  $v \in N$  belongs to one of these three categories. To be able to define line connections for the timetable planning, not only the frequencies of the lines are needed, but also the information at which stations and how many passengers change to connecting lines. For this reason and to avoid frequent line transfers of passengers at transfer stations, the CGN is used in addition. The CGN will be built based on the given line pool and the PTN.

Like the PTN, the CGN is an undirected graph based on connected vertices represented by network stations. In addition, at each station and for each line serving that station, an interchange node is inserted and connected to the station nodes by a connecting edge. Further, these transfer nodes are then connected by driving edges to the transfer nodes of the nearest station served by the lines (see Table 1 for an example). These driving edges between consecutive nodes  $v_{k-1}^l$  and  $v_k^l$  of line  $l$  are weighted by the minimal travel time  $t_{trip}^{k-}$  plus the minimal dwell time  $t_{dwell}^{(k-1)-}$  at node  $v_{k-1}^l$ , of line category corresponding to line  $l$ . Both times can be computed from infrastructure data (e.g. by using the length of a track-section and the technical speed restriction). Transfer edges receive weights  $\theta^+$ , which represent passenger transfer times between two lines serving node  $v_k$ .

Based on the OD demand and the CGN, the shortest routes can now be determined from all nodes  $v_{k_1}$  to all nodes  $v_{k_2}$  in the network  $N$ , thereby calculating the number of passengers on each edge  $e \in E$  of the PTN and also on the transfer edges in the CGN. Furthermore, with this edge demand  $w_e$  and the capacity  $Cap$  of the trains, the minimum frequency per edge  $e \in E$  can be calculated from  $f_e^{min} := \left\lceil \frac{w_e}{Cap} \right\rceil$ . On the other side,  $f_e^{max}$  is given as the maximum slot capacity of edge  $e \in E$ , which depends on properties of the track infrastructure, safety restrictions (mainly headways) and planned rolling stock of the different line categories.  $f_e^{min}$  and  $f_e^{max}$  are used as input for determining the lines and their frequencies.

The problem *LineP* is the basic cost model for line planning:

$$\begin{aligned} \min \quad & \sum_{l \in \mathcal{L}_0} cost_l f_l, \\ \text{s. t. } \quad & f_e^{max} \geq \sum_{l \in \mathcal{L}_0; e \in l} f_l \geq f_e^{min}, \quad \forall e \in E, f_l \in \mathbb{N}, \forall l \in \mathcal{L}_0 \end{aligned} \tag{1}$$

and  $cost_l$  being the fixed cost of operating line  $l$ .

*LineP* results in the minimum and hence most cost-effective number of vehicle trips per line, which satisfies the given demand. The selected lines together with its frequencies, minimum trip and dwell times, start and end locations (turnaround), and transfer conditions represent the SI. In the proposed approach the connection and time dependency conditions in the SI can be derived from the passenger assignment step and the resulting travel chains (i.e. the transfer edges).

## 2.2 Generation of the SI

In the first part of this section, we give a short introduction to the notation of the SI. For details, we refer to Caimi (2009). According to Caimi, the periodic SI for a given railway network is defined as  $\mathcal{G} = (T, Z, C, D)$ , where  $T \in \mathbb{R}^+$  is the considered time period (equal to the time period we used in section 2.1),  $Z$  the set of all periodic train runs,  $C$  the set of all connections and  $D$  the set of all dependencies. A train run  $z \in Z$  is defined as the run over  $K + 1$  nodes in the topology, repeated  $R$  times with periodicity  $\rho$  minutes:

$$z = \left( (v_k, t_{\text{dwell}}^{k-}, t_{\text{dwell}}^{k+}, t_{\text{trip}}^{k-}, t_{\text{trip}}^{k+}, \omega_k^-, \omega_k^+)_{k=0}^K, \rho, R \right),$$

where  $v_k \in N$  is the node visited in the  $k$ -th step of the train run. We associate an arrival event  $\text{arr}_z(v)$  and a departure event  $\text{dep}_z(v)$  to each node  $v \in N$  on the train run  $z$ .  $t_{\text{dwell}}^{k-/+}$  is the minimal and maximal dwell time of the train between the arrival  $\text{arr}_z(v_k)$  and  $\text{dep}_z(v_k)$  (a value of zero means that the train passes the node without stopping),  $[t_{\text{trip}}^{k-}, t_{\text{trip}}^{k+}]$  defines the allowed interval of the trip time between  $\text{dep}_z(v_{k-1})$  and  $\text{arr}_z(v_k)$ , and  $[\omega_k^-, \omega_k^+]$  is the (optional) time slot for the departure event of the first train recurrence.

A connection  $c = (z_1, z_2, v, r_1, r_2, \theta^-, \theta^+)$ ,  $c \in C$ , is defined as the possibility for the passenger to change from train run  $z_1$  to train run  $z_2$  in station  $v \in N$ . The connection takes place for the first time during the  $r_1$ -th repetition of train run  $z_1$  and the  $r_2$ -th repetition of train run  $z_2$  between  $\theta^-$  and  $\theta^+$  minutes, i.e. the arrival event  $\text{arr}_{z_1}(v)$  should take place at least  $\theta^-$  resp. at most  $\theta^+$  minutes before the departure event  $\text{dep}_{z_2}(v)$ .

A time dependency  $d \in D$  is defined as a time constraint between two nodes of the periodic service intention, where  $d = (z_1, z_2, e_z(v_{k_1}), e_z(v_{k_2}), r_1, r_2, \theta^-, \theta^+)$  and  $e_z(v)$  is an arrival or a departure event associated to a node  $v \in N$  on train run  $z$ . Again, the event  $e_z(v_{k_1})$  of the  $k_1$ -th node of train run  $z_1$  should occur between  $\theta^-$  and  $\theta^+$  minutes before the event  $e_z(v_{k_2})$   $k_2$ -th node of train run  $z_2$ . The dependency takes place for the first time during the  $r_1$ -th repetition of train run  $z_1$  and the  $r_2$ -th repetition of train run  $z_2$ .

At next, we explain how the SI is generated. We state that we get from the line planning step (a) in section 2.1 all information required for constructing the SI. To illustrate our approach, we consider two lines  $l_1$  and  $l_2 \in \mathcal{L}_0$  from the output of the line planning. The lines  $l_i = (v_0^{l_i}, \dots, v_K^{l_i})$  are operated with frequency  $f_i$  for  $i = 1, 2$ . Without loss of generality, there should be a transfer from line  $l_1$  in direction of the end node  $v_K^{l_1}$  to  $l_2$  in direction of the end node  $v_0^{l_2}$  at the common node  $v_K^{l_1} = v_K^{l_2}$ , which should take place in at most  $\theta^+$  minutes.

First the lines  $l_1$  and  $l_2$  generate four train runs (two in each direction)

$$z_i = \left( (v_k^{l_i}, t_{dwell}^{k-}, t_{dwell}^{k+}, t_{trip}^{k-}, t_{trip}^{k+})_{k=0}^K, \frac{T}{f_i}, f_i \right) \quad (2)$$

$$z_{2+i} = \left( (v_k^{l_i}, t_{dwell}^{k-}, t_{dwell}^{k+}, t_{trip}^{k-}, t_{trip}^{k+})_{k=K}^0, \frac{T}{f_i}, f_i \right) \quad (3)$$

for  $i = 1, 2$ . Train run  $z_{2+i}$  runs in the opposite direction of train run  $z_i$ , both being part of line  $l_i$ . The upper bounds of the trip time  $t_{trip}^{k+}$  and the dwell time  $t_{dwell}^{k+}$  are computed from the lower bounds by multiplying them with a (individual) constant factor. These time intervals will be used to compute flexible and stable plans (see section 2.3 and section 3 for details). The range of these intervals have to be adapted to the given track topology.

We use time dependencies to separate the departure events in the repetitions of train run  $z_i$ ,  $i = 1, 2$ , during time period  $T$  by exactly  $\frac{T}{f_i}$  minutes, namely

$$d = \left( z_i, z_i, dep_{z_i}(v_{k_j}^{l_i}), dep_{z_i}(v_{k_j}^{l_i}), r_m, r_{m+1}, \frac{T}{f_i}, \frac{T}{f_i} \right)$$

at each node of  $v_{k_j}^{l_i}$ ,  $0 \leq k_j \leq K$  on the train run  $z_i$  and for each repetition  $r_m$  with  $1 \leq r_m \leq (f_i - 1)$ . Of course, we can also add some time tolerance in the departure times between repetitions.

We also introduce a certain service level for the length of travel times. This is achieved by defining time dependencies that force the travel times between the first and the last node of each line to be not longer than  $\alpha$  ( $\geq 1$ ) times the minimum travel time, i.e. for each train run  $z_i$ ,  $i = 1, 2$ , we have

$$d = \left( z_i, z_i, arr_{z_i}(v_0^{l_i}), arr_{z_i}(v_K^{l_i}), r_m, r_m, \sum_{k=0}^K (t_{dwell}^{k-} + t_{trip}^{k-}), \alpha \left( \sum_{k=0}^K (t_{dwell}^{k-} + t_{trip}^{k-}) \right) \right) \quad (4)$$

and the same for the train runs in the opposite direction  $z_i$ ,  $i = 3, 4$ ,

$$d = \left( z_i, z_i, arr_{z_i}(v_K^{l_i}), arr_{z_i}(v_0^{l_i}), r_m, r_m, \sum_{k=0}^K (t_{dwell}^{k-} + t_{trip}^{k-}), \alpha \left( \sum_{k=0}^K (t_{dwell}^{k-} + t_{trip}^{k-}) \right) \right) \quad (5)$$

for each repetition  $r_m$  with  $1 \leq r_m \leq f_i$ .

Our timetabling model TCFPESP (see section 2.3) therefore is flexible to adjust travel times between two consecutive nodes, but it must respect this restriction of the total travel time. This property can be used to make the timetable more robust (see Wüst et al. 2019).

Turnaround conditions at both ends of each line can also be implemented using time dependencies. We get each for train run  $z_i$ ,  $i = 1, 2$ ,

$$d = (z_i, z_{2+i}, dep_{z_i}(v_K^{l_i}), arr_{z_{2+i}}(v_0^{l_i}), r_m, r_m, \theta^-, \theta^+)$$

$$d = (z_{2+i}, z_i, dep_{z_{2+i}}(v_0^{l_i}), arr_{z_i}(v_K^{l_i}), r_m, r_m, \theta^-, \theta^+)$$

and each repetition  $r_m$  with  $1 \leq r_m \leq f_i$ .  $\theta^-$  represents the (technical) minimum turnaround time needed at the end node  $v_K^{l_i}$  resp  $v_0^{l_i}$  of line  $l_i$ .  $\theta^+$  and can be used to control the minimum number of rolling stock needed to execute the timetable. In this case  $\theta^+$  is depending on the total trip times between the starting and the end node of the line and can be computed according to the approach described in Liebchen (2007).

Transfer conditions from the line planning step are natural candidates for connections since they represent the travel chains of the passengers. In the line planning step we get a transfer possibility from train run  $z_1$  to train run  $z_4$  at common node  $v_K^{l_1}$  (see assumption at the beginning of this section), but we don't fix explicitly at which concrete repetition of the lines these transfer should take place. The repetition is obvious, if the frequency  $f_i$  is equal to 1 for  $i = 1, 2$  or if for some higher reasons the repetitions are fixed. We therefore distinguish two cases:

a) The repetitions of the train runs for the transfers are **known**:

The transfer from train run  $z_1$  at repetition  $r_m$ ,  $1 \leq r_m \leq f_1$ , to train run  $z_4$  at repetition  $r_n$ ,  $1 \leq r_n \leq f_2$ , takes place at node  $v_K^{l_1}$  in at most  $\theta^+$  minutes. Based on this assumption, we generate the following SI-connection:  $c = (z_1, z_4, v_K^{l_1}, r_m, r_n, \theta^-, \theta^+)$ ,

The lower bound  $\theta^-$  minutes is a minimum time needed for the transfer. This bound is given by the walking distance of the platforms of the connecting lines at the transfer node.

b) The repetitions of the train runs for the transfers are **not known**:

In this case, we generate time dependencies in the SI, which configure the model in such a way that for a certain combination of repetitions of train runs  $z_1$  and  $z_4$  a feasible solution with connections can be found. This approach is described in Peeters (2003). We demonstrate this approach for the case of  $f_1 = 1$  and  $f_2 = 2$ . The transfer therefore should take place between

repetition  $r_1$  of train run  $z_1$  and repetition  $r_1$  of train run  $z_4$  or  
repetition  $r_1$  of train run  $z_1$  and repetition  $r_2$  of train run  $z_4$

This or-condition can be transformed into two time-dependencies. This is possible mainly due to the consideration of a periodic timetable. The transfer should take place in the time interval  $[\theta^-, \theta^+]$ , where  $\theta^-$  again corresponds to the minimum time needed for the transfer at the considered node.



In Peeters (2003) they give the following proposition. We assume that  $(\theta^+ - \theta^-) \leq \frac{T}{f_2}$  holds. If the four time-dependencies

$$d = \left( z_1, z_4, \text{arr}_{z_1}(v_K^{l_1}), \text{dep}_{z_4}(v_K^{l_2}), r_1, r_m, \theta^-, \theta^+ + \frac{T}{f_2} \right) \quad (6)$$

$$d = \left( z_1, z_4, \text{arr}_{z_1}(v_K^{l_1}), \text{dep}_{z_4}(v_0^{l_2}), r_1, r_m, \theta^- + \frac{T}{f_2}, \theta^+ + T \right) \quad (7)$$

for  $m = 1, 2$  are fulfilled, then exactly one of the repetitions  $r_1$  and  $r_2$  of train run  $z_4$  allow a transfer from train run  $z_1$  in the time interval  $[\theta^-, \theta^+]$ .

The assumption  $(\theta^+ - \theta^-) \leq \frac{T}{f_2}$  is not too strong. If this assumption is not fulfilled, we just could wait for the next repetition of the train instead of forcing a connection.

Approach b) above prevents the combination of the “wrong” repetitions a priori, which could lead to an infeasible SI (see also section 3).

### 2.3 Generation of the timetable in the planning step (b)

For generating the timetable, we use a model for generating flexible periodic timetables based on a mesoscopic resolution of track infrastructure and safety configurations. This model is called TCFPESP and has been described in detail recently (see Wüst et al. 2018 and Wüst et al. 2019). The input to this model is given by the SI. If the SI is logically consistent and feasible in terms of the model configuration, a timetable can be generated. For detecting conflicts, we make use of the approach of Polinder et al. (2018). They can identify possible relaxations in an infeasible SI. In the case of maintenance work, the result of the line planning step leads to an inconsistent SI. We did relax some of the computed transfers to get a feasible SI with the approach of Polinder (see section 3 for details). Besides the timetable itself, the output also contains the train-track assignment. The output is described in more detail in Wüst et al. (2019). In this article, we focus on the description of the input configuration for generating the SI and how this input configuration is generated from the result of the line planning step.

## 3 Real World Case Study

### 3.1 Delineation of the case study

To illustrate the line planning algorithm on a real-world example, we have selected a railway corridor in eastern Switzerland. Referring to the geographical location of the corridor, we call the case study “Kerenzerberg” (see Figure 1). The infrastructure (i.e. the

PTN), the minimum travel time and the line pools of the line categories are read out from the timetable valid in the year 2018. The OD-demand between the considered stations is constructed manually in such a way that the lines operate with the frequencies of the actual timetable. A total of 23836 passengers have to be transported in the considered hour. With this case study, we want to demonstrate how we iteratively adapt a reference timetable to a timetable with maintenance work on a track section in the network corridor by re-executing line planning step (a) considering the restricted resource conditions. In this case, one of the two tracks of the section between the nodes Flums and Mels is completely blocked. With this constraint, a feasible temporary timetable in planning step (b) can only be constructed if the SI is relaxed in terms of the number or kind of operated lines. A change in the resulting line plan induces changes of the passenger flows. Based on this line plan as input a temporary timetable for the maintenance interval is calculated with the objective e.g. to minimally reduce the overall passenger travel time and at the same time respect the arrival and departure times of the reference timetable as much as possible.

### 3.2 Network segmentation, station and line categories

To avoid making timetable changes at locations that have no or negligible influence on the solution, it is important to identify which part of the entire rail network needs to be adapted and which part can be assumed to remain as specified in the reference timetable. Therefore, in a first step, the relevant lines of the subnetwork that will be directly affected by the construction sites must be identified. In a second step, all lines which are coupled (e.g., by transfers or technical dependencies) to the directly affected lines have to be identified. The relevant rail network is subdivided into two subnetworks, as shown in figure 1. First one identifies the subnet nodes that isolate the relevant infrastructure partitions from the periphery with fixed timetable times. In this way, we separate the disaggregated subnetwork with the relevant infrastructure segments from an aggregated subnetwork with fixed timetable and infinite capacity. All train movements are planned in detail on the disaggregated subnetwork. For each line coming from or going beyond the boundary nodes of the disaggregated subnet, we create a virtual end station node. In order to ensure that the different line categories stop at the right stations also in case of creating new lines that take reduced track capacity into consideration, stations are associated to line categories as shown in Table 1. Furthermore, we need this categorization to perform the ‘system split’ according to Oltrogge (1994).

Table 11: Stations, lines with their categories (IC (intercity), IR (interregio) and S-Bahn (commuter)) and their turnaround times under normal operations.

Stops / Line categories		Zürich HB (ZHB)	Richterswil (RW)	Glarus (GL)	Uznach (UZ)	Ziegelbrücke	Mühlehorn (MH)	Tiefenwinkel	Murg (MG)	Unterterzen (UNT)	Mols (MOL)	Walensdorf (WAL)	Flums (FMS)	Mels (MEL)	Sargans (SA)	Sewelen (SE)	Buchs (BU)	Maienthal (MF)	Chur (CH)	Line rotation time
IC	IC3	x													x				x	178
	RJ	x													x		x			162
IR	RE1	x				x						x			x				x	182
	RE2														x		x		x	62
S-Bahn	S2	x	x			x														106
	S4				x	x	x	x	x	x	x	x	x	x	x	x	x			98
	S6			x	x	x									x			x	x	50
	S12																			42
	S25	x	x	x		x														134

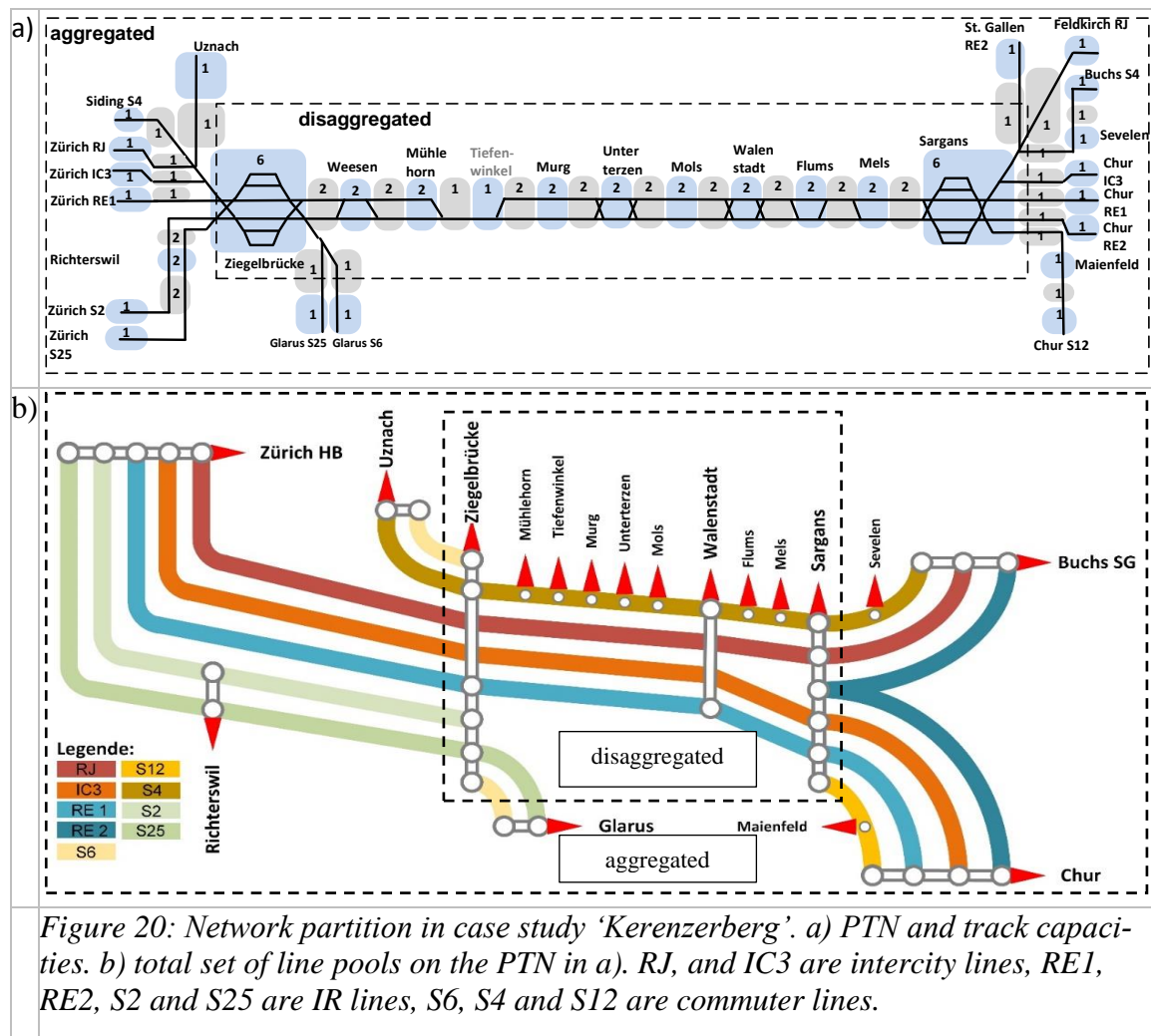
The sum of all trip times along the line sections in both directions, the dwell times at the stations and the required turnaround times at the final stations results in the line rotation time which is indicated in the last column of Table 1. Because the planned maintenance work is located on the network section between stations Flums and Mels between the transfer nodes Ziegelbrücke and Sargans, we decided to use this corridor as a disaggregated partition of the test network. The western part of Ziegelbrücke and the eastern part of Sargans are aggregated. See Wüst et al. (2018a) for more details on the partitioning of the network.

### 3.3 Generation of a reference line plan and the corresponding timetable

We apply the line planning model LineP (equation 1) to each line pool (IC, IR and S-Bahn) separately. We assume costs per line are equal, i.e. we minimize the sum of all

frequencies of the lines selected by the line planning model. The maximal transfer time is 10 minutes between the lines. The computed frequencies of the model *LineP* for all lines are the same as in the timetable valid in the year 2018. The frequencies of the lines passing the corridor between Ziegelbrücke and Sargans are shown in Figure 22a.

We combined all selected lines of all line categories from the line pools in one CGN (see Figure 2). The thickness of the lines in Figure 2 corresponds to the passenger loads. The white nodes represent the individual stations of the network partition. These are connected to the transfer nodes of the lines that connect these stations by the transfer edges. F1 to F30 represent the driving edges. 40 transfer edges between lines at different stations and a total of 2520 transfer passengers resulted from the line planning step (see Figure 3 and Table 2 for important transfer edges in Walenstadt).



We generated the SI by using the approach described in section 2.2. For the upper bounds of travel and dwell times in (2) and (3) we multiplied the minimum times with 1.5. For the time dependencies in (4) and (5) we set  $\alpha$  equal to 1.2. We parametrized the TCFPESP with this SI and could generate a feasible, reference timetable (see Figure 4). We could, therefore, guarantee all (40) connections of the SI within a maximum of 10 minutes.

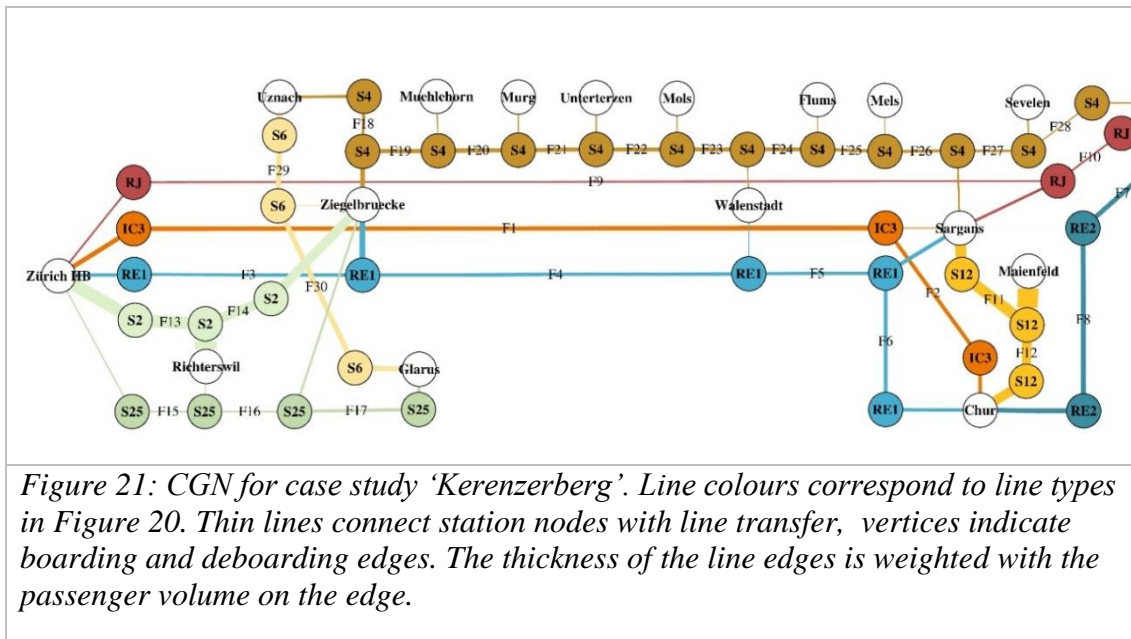


Figure 21: CGN for case study 'Kerenzerberg'. Line colours correspond to line types in Figure 20. Thin lines connect station nodes with line transfer, vertices indicate boarding and deboarding edges. The thickness of the line edges is weighted with the passenger volume on the edge.

### 3.4 Generation of line plan and a timetable for a time period with maintenance work

Restricting the section between Flums and Mels due to a site-specific track blocking results in only one track available. We want to generate a timetable for this timetable period with maintenance work, but we only admit a time tolerance of  $\pm 3$  minutes with respect to the departure times of the reference timetable. With this restriction and the reduced infrastructure, the TCFPESP becomes infeasible. In Figure 23 one can see that there are two crossings of lines between Flums and Mels, such that the reference timetable itself is not feasible any more. Next we tried to relax the constraints with the approach of Polinder et al. (2018). The effect on the quality of the timetable with respect to passenger travel times was not acceptable. Therefore, we decided to go back to planning step (a, line planning). We had to change the line pool in order to reduce the number of lines crossing the section between Flums and Mels.

One solution, for example, is to delete the edge F25 of the lowest category S4 between Flums and Mels (see Figure 21) and introduce two new independent line fragments S4.1 and S4.2. These new lines now operate between Uznach and Flums in the western part and between Mels and Buchs in the eastern part. Hence, line S4 no longer crosses the affected section. We used the given OD-matrix and the new (reduced) line pool of the commuter lines to resolve the line planning model *LineP* (with the same costs and transfer times as in the reference case). Except for line S4 all other lines operate with the same frequencies as before. The new fragment lines S4.1 and S4.2 operate with frequency 1 (see Figure 22). We compare the line planning output of the reference case for the normal operation and the operation with the maintenance interval.

**Passenger flows:** Since the S4 in the maintenance interval no longer runs between Flums and Mels, some passengers are forced to change in Sargans or Walenstadt. This can be seen from the line widths of the individual edges in Figure 22, which are scaled with the number of passengers. Those passengers, who have used the S4 for transport between Flums and Mels in normal operation, change to the line RE1 in construction site operation. This is illustrated in Figure 22 for the reference line plan (a) and can be compared to the line plan for the maintenance interval (b).

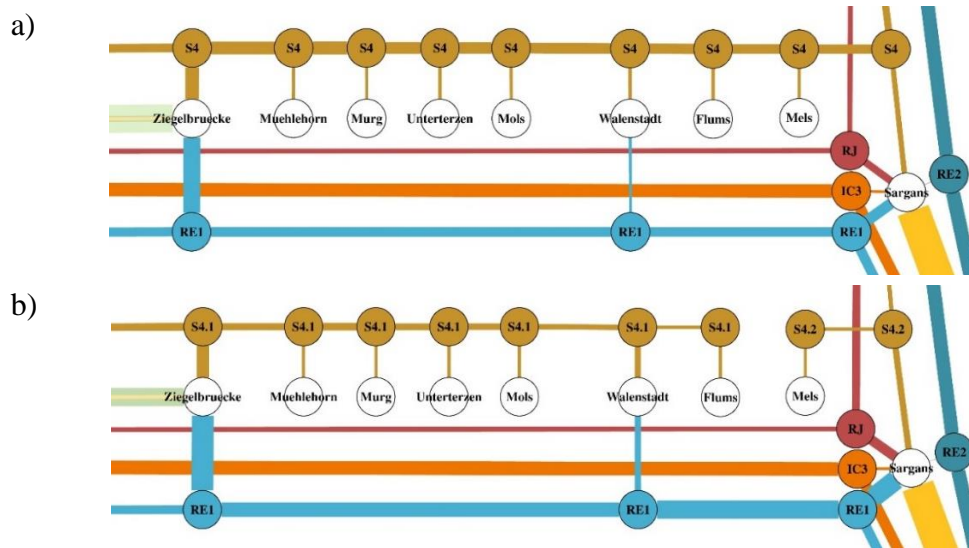


Figure 22: Passenger flow (a) in the case of the reference line plan and (b) in case of period with maintenance work

**Transfer connections:** In Figure 3, the passenger flows are illustrated across lines and nodes. Additionally, the transfer edges can be identified. Forty transfer edges between lines at different stations and a total of 2520 transfer passengers resulted from the line planning step under normal operations. For the maintenance line plan, we get a total of 51 transfer edges with 3806 transfer passengers. The transfer edges are an important input to timetabling to specify connections between train runs (see section 2.2). In Table 2 these are shown by the example of Walenstadt station. In parentheses, the predecessor or successor stations are indicated. The increase from a total of 132 transfers in normal operation to a total of 444 transfers in the maintenance interval represents the impact of the construction site on the transfers in Walenstadt to the RE1. **Operation costs:** Using line rotation times and line frequencies and the fixed costs of the line, the operating costs could be calculated. For the duration of the maintenance time window thus any additional costs could be determined. As mentioned above, in our calculations, we assumed cost rates to be equal. We therefore refrain from presenting the costs.

Walenstadt (normal operations)			Walenstadt (operation period with maintenance work)		
From	To	Number of passengers	From	To	Number of passengers
RE1 (Ziegelbrücke)	S4 (Flums)	40	RE1 (Sargans)	S4 (Mols)	134
S4 (Flums)	RE1 (Ziegelbrücke)	40	S4 (Mols)	RE1 (Sargans)	134
RE1 (Sargans)	S4 (Mols)	26	RE1 (Sargans)	S4 (Flums)	68
S4 (Mols)	RE1 (Sargans)	26	S4 (Flums)	RE1 (Sargans)	68
RE1 (Ziegelbrücke)	S4 (Flums)	20	RE1 (Ziegelbrücke)	S4 (Flums)	20
S4 (Flums)	RE1 (Ziegelbrücke)	20	S4 (Flums)	RE1 (Ziegelbrücke)	20
<b>Total:</b>		<b>132</b>	<b>Total:</b>		<b>444</b>

Table 12: transfer connections for line plan with normal operations (left) and operation period with maintenance work (right)

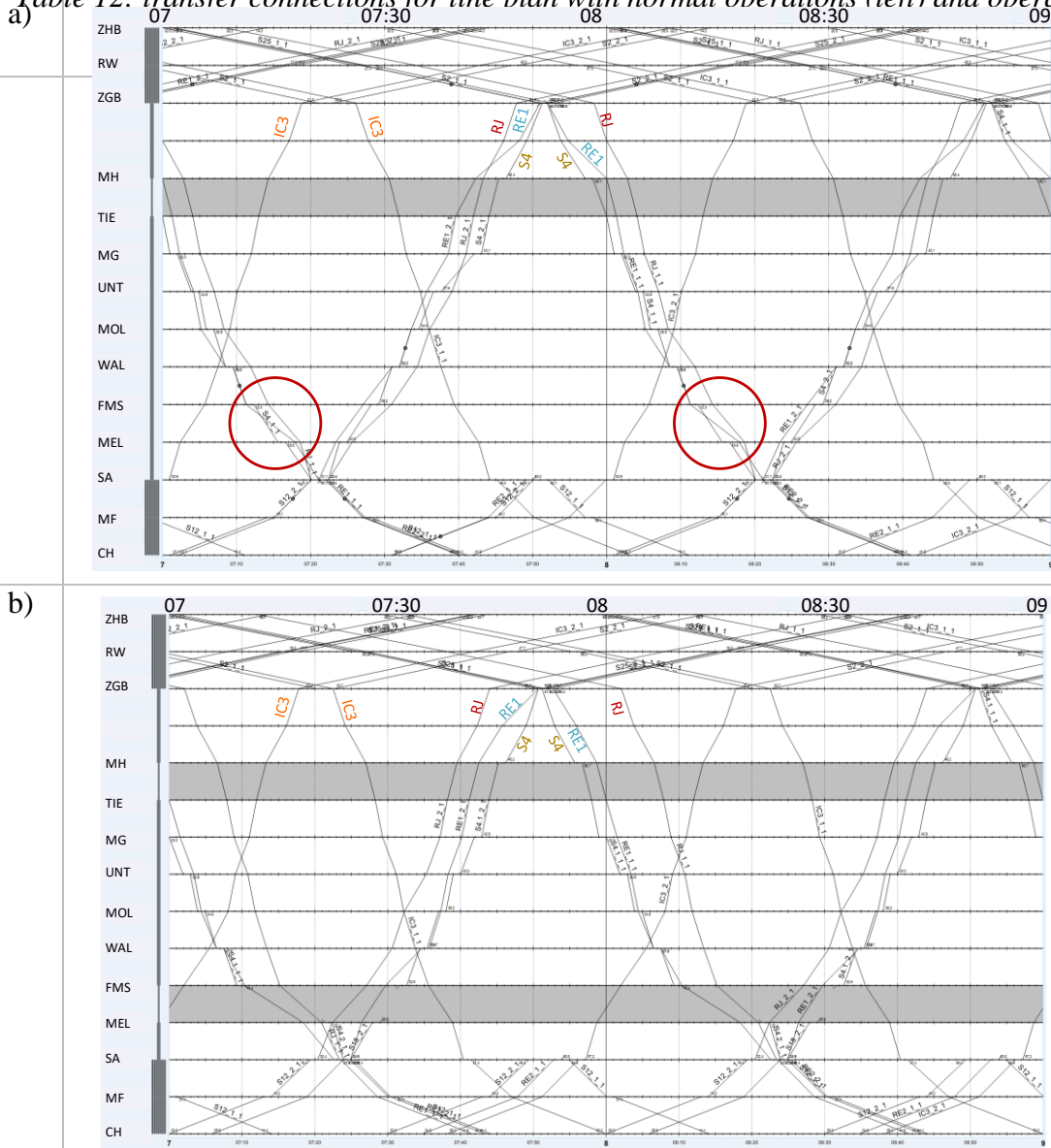


Figure 23: Graphical timetable for corridor 'Kerenzerberg'. a) normal operations, red circles indicate overtaking trains between Flums and Mels; b) operations with track

*maintenance work between stations Flums and Mels. No train overtakings occur on this section any more.*

From the output of the line planning step in the maintenance interval, we generate the SI again according to section 2.2. The factors in (2)-(5) are the same as in the reference case. As described before we only admit a time tolerance of  $\pm 3.75$  minutes concerning the departure times of the reference timetable. We added these constraints to our TCFPESP model. In the first run, the TCFPESP model became infeasible. We used again the approach of Polinder et al. (2018) to determine how much we have to loosen the constraints to become feasible. We admitted only the connection constraints related to (6) and (7) to be relaxed.

Furthermore, we used the transfer passengers as weights in the objective of the model of Polinder. The result was to relax 6 of the 51 transfers times related to constraints (6) and (7) (one to 17, 4 to 33 and one to 55 minutes). Since this only affected 226 of 3806 transfer passengers, we accepted the timetable (see Figure 23b). In Figure 23, we can compare the two timetables. The conflicts between Flums and Mels disappeared due to the new lines S 4.1 and S 4.2. Furthermore, all the lines without line S4 are in a time band of  $\pm 3.75$  minutes compared to the reference case.

To assess the convenience impact for passengers one can either calculate the increase in travel time for all passengers or the travel time of those who are affected by the construction site otherwise. Passengers concerned are those who travel in normal operation with the S4 between Flums and Mels (edge F25 in Figure 21). For all passengers, the weighted travel times with the maintenance timetable is only 1% higher than with the reference timetable. For the affected passengers, the overall increase in the weighted travel time amounts to 24%. In Table 3 we illustrate travel times for some selected origin-destination combinations.

*Table 13: Selected travel times for both line planning scenarios*

Travel times				
From	To	Reference timetable	Timetable with maintenance interval	Extension
Flums	Mels	5	57	1020%
Ziegelbrücke	Mels	30	37	23%
Chur	Flums	28	64	156%
Zürich HB	Chur	89	92	3%



## 4 Summary and Conclusions

Line planning is a fundamental step in the creation of a transport service. By automating this planning step, different scenarios can be compared with each other within a short time. From these scenarios, cost-effective timetables can be derived. Above all, schedule deviations due to construction sites and disruptions are virtually unmanageable in the multitude of operations. In cooperation between SBB and ZHAW, a process for automated line planning was developed, which provides fast solutions to such capacity limitations. The deletion of the edge F25 (i.e., the division of the S4 into two sub-lines) was still done manually and justified with the small priority of the S4. Currently, the project team is also working on a method for line pool generation, which will create an option to automate this step in the future as well (see Gattermann et al., 2017). The case study "Kerenzerberg" illustrates how the affected network partition can be divided into an aggregated and disaggregated subnetwork and how the use of Change & Go network resp. the line planning model produces the SI for the timetabling model. The results are highly dependent on the quality of the OD-matrix, which should be continually improved by surveying customer movements. Rather than trying to generate a reference timetable that is as close as possible to the actual timetable in the corridor of the case study, we focused on putting together the methods that are involved in the process of the line planning and timetabling steps. For the definition of our SI, we neglected the requirement for cargo trains, time dependencies of far distance trains in the hubs of Zürich and Chur as well as operational conditions that we did not know about. For this reason, we think that a direct comparison of the resulting timetable with the actual timetable is not meaningful. However, we could demonstrate the impact of the relevant practical requirements on automated timetabling even for situations of reduced resource availability.

Finally, the information gained from our proposed line planning and timetabling methods are not limited to line frequencies and their associated travel times and operating costs. By supplementing the results with the passenger flows and transfer connections, an important added value for ensuring line transfers in the timetable planning step can be created.

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