Generating timetables for a multi-linetype public transport offer based on a service intention including travel chains of customers

Stefano Gioia
Stephan Bütikofer
Raimond Matthias Wüst

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Stefano Gioia
Institute of Data Analysis and Process Design
ZHAW, Switzerland
Institute for Transport Planning and Systems
ETH Zurich, Switzerland
E: gioi@zhaw.ch

Stephan Bütikofer
Institute of Data Analysis and Process Design
ZHAW, Switzerland
E: buts@zhaw.ch

Raimond Matthias Wüst
Institute of Data Analysis and Process Design
ZHAW, Switzerland
E: wura@zhaw.ch

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Abstract

In public transport, fulfilling passenger demand and resulting passenger travel chains with different linetypes requires an exact coordination of passenger transfers between the suited elements of the offer. In order to generate a customer-oriented offer, we implement a standard network design technique, known as *system split*, where the allocation of given OD passenger demand is based on travel chains, whose components are *linetype-specific* edges. Such a decomposition of the overall passenger demand into linetype specific subsets allows the calculation of the line plan for each linetype-specific sub-network, which is done with the help of the open-source software LinTim. The computed line plans and the information of the travel chains are translated into a *service intention* defining all elements of the public transport offer. In a further step this service intention will be used to configure an event-activity network (resp. a PESP model) including all linetypes, thus extending the functionality of LinTim. Specifically, the timetables of the different linetypes are coordinated by considering the passenger transfers in the travel chains resulting from the system split. The obtained PESP model is then used to compute the timetable again in LinTim. The approach is illustrated in a small, realistic scenario near Lucerne in order to discuss and validate the results.

Keywords

Timetable generation, multi-type line planning, demand modeling

1. Introduction

The public transport offer consists of a timetable for various train runs belonging to several linetypes (or *line types*, e.g. regional, interregional or intercity), which provide different levels of service to the passengers. A linetype is mainly defined by the different stopping patterns. The expected passenger demand at each stop and the distances between the stops play a central role in determining the stopping patterns for the linetypes. Both the number of stops and the distances between stops contribute to the achievable speed for passengers and the distance range of train runs per linetype.

The timetable is the final and detailed specification of the offer, based on a framework consisting of train runs and relationships between them (e.g. time intervals to be maintained between repetitions of train runs belonging to the same line). This formal framework was introduced in the literature as *service intention* (*SI*) by (Caimi, 2009; Wüst et al., 2008). The SI includes technical and commercial parameters. Technical line properties are represented by linetypes and trip times. Commercial properties include dwell and transfer times and thus represent customer relevant service levels. In this work we focus on the passenger transfer relations, which are an important class of relations in the SI between train runs. By coordinating passenger transfer relations, it becomes possible for passengers to have one or more attractive travel chains between the origin and destination of their trip. A travel chain represents a route option for the passengers. These transfer relations are therefore an important quality measure of a timetable resp. of the entire service. The knowledge of these travel chains is also of great interest in the event of a disruption, for example, as it allows to detect the importance of a passenger transfer relation (i.e. how many expected passengers are affected by a disruption of a transfer relation).

The SI and thus also the passenger transfer relations are created in the strategic planning over a long planning horizon in cooperation between the rail operator and the infrastructure manager. Strategic planning is often only partially automated and also includes manual steps (see e.g. Fuchs et al., 2021; Amstutz, 2019). The typical, strategic planning steps are (see e.g. Bussieck, 1998; Goossens et al., 2006; Michaelis and Schöbel, 2009; Schöbel, 2012):

(1) network design, (2) line planning and (3) timetabling

A possible modelling approach of these steps is part of this work and is described in detail in Section 2.

In network design, the number of linetypes to be operated on the given infrastructure network and the linetype characteristics are decided. Furthermore, stops are assigned to the linetypes and thus also which stops are connected with which linetype edges. With the help of a route choice model (Barcelo, 2010) the given, expected demand per period is assigned between an origin and a destination to one or more routes. As a result, an expected load on the edges of the linetypes is created. This allocation happens before there are concrete lines or a timetable. The lines are formed later in the line planning step. A route here consists of a sequence of edges that belong to a linetype (e.g. passengers travel from A to B with the linetype regional and from B to C with the linetype intercity). Thus, a route represents a travel chain in which certain passenger transfer relations are assumed (in the example, there is a transfer relation in B between the linetypes regional and intercity). The result of network design is a network of stops and edges for each linetype and a corresponding passenger demand split per linetype.

In the second step, line planning, the line routes (per linetype) and their frequencies per time period are determined. The lines often run between two end points in both directions. A distinction is made here as to whether line planning is performed per one linetype (single type line planning) or for all linetypes together (multi-type line planning). A comparison of both approaches is described in Goossens et al. (2006). In line planning passenger demand is reassigned to travel chains again, often based on the shortest path between origin and destination. This is necessary because the lines available for selection may not use all linetype edges and therefore the travel chains assigned before in network design are not feasible anymore (this may happen if several routes are available between two stops). In line planning further passenger transfer relations are therefore defined within the linetype (in the example above, it might be necessary to have a transfer from one regional line to another regional line on the way from A to B).

In the third step, timetabling, (periodic) times for all arrival and departure events of the train runs are determined. These times should fulfil the requirements of the generated SI. Thus, the calculated timetable is a feasible realization of the SI-specification. The passenger transfer relations, which are necessary for the realization of the passenger travel chains, have thereby been determined in the previous steps of network design and line planning.

The goals of this work are:

- the mathematical modelling of the strategic planning steps network design, line planning and timetabling with a focus on the emergence and the definition of passenger travel chains. Different modelling approaches exist for the individual steps (see also literature discussion below), the challenge here is to achieve a consistent interaction of these steps (by performing network design, line planning and timetabling under the same assumptions).
- illustrating the emergence of a travel chain up to the timetable on a small example in the Lucerne area. Demonstrating the added value of this approach, which allows to distinguish between planned and unplanned transfers.

There are many different modelling approaches for the individual steps in strategic planning described in the literature. We give here the approaches that are relevant for us.

For network design in public transport a *system split* technique has been introduced by (Oltrogge, 1994). This technique distributes the given, estimated OD demand per time period over different routes. The passenger load of each travel chain is estimated with a suited utility-function based demand choice model (Barcelo, 2010). A decision support tool including the system split approach was used by dutch railways (Hooghiemstra et al., 1999). In the literature the implementation of the system split technique is an often-used assumption before the line planning step (e.g. Borndörfer 2008; Schöbel, 2012). An overview of other approaches in network design of public transport systems can be found in (Ceder, 2002).

In line planning most of the works focus on single type line planning problems (see e.g Schöbel, 2012, for an overview), i.e. for each linetype a line planning problem is solved. Therefore, additional coordination between the linetypes is needed before computing a timetable (see Section 2). Depending on the objective one distinguishes furthermore between customer-oriented resp. operator-oriented models (Schöbel, 2012). By our knowledge there is only little literature related to multi-type line planning (Goossens et al., 2004; Goossens et al., 2006; Borndörfer, 2008). In (Goossens et al., 2006) the line plan and the allocation of passengers to routes are computed simultaneously, with the objective of minimizing the operated train capacities and operational costs. In (Goossens et al., 2004) a method to minimize the total travel time of passengers by altering the stops of the lines for a given line plan is introduced.

In the timetabling step we make use of the Periodic Event Scheduling Problem (PESP) introduced by (Serafini and Ukovich, 1989). The modelling possibilities in public transport of the PESP models are described in (Liebchen et al, 2007). Whereas different approaches for solving this problem are discussed e.g. in (Liebchen et al, 2008; Herrigel et al., 2018; Jordi et al., 2019). The formal concept of the SI was first introduced by (Wüst et al., 2008). In (Caimi, 2009) it is shown that the PESP model can be parametrized completely by the SI.

Different modelling and solution approaches for single type line planning problems and timetabling are implemented in the open-source software LinTim (Schiewe et al., 2020). We will make use of LinTim to perform the numerical experiments (see Section 3). It is worth mentioning again, that our focus is not on the modelling of the single strategic planning steps. We try here to work on the interface of the models in such a way that the passenger travel chains are realized in the timetable.

The remainder of the paper is structured as follows. Section 2 describes the modelling of the strategic planning steps. The development of the passenger travel chains during these steps and an approach to integrate the travel chains into the service intention are demonstrated. Section 3 illustrates this approach in a small, realistic scenario around Lucerne. Conclusions and future directions are discussed in Section 4.

2. Methods

2.1 Outline

In the following sections, the methods related to the planning steps are described in detail. It is shown how they are integrated to finally obtain a timetable complying both with the assumed travel chains and demand allocation. It is illustrated how to obtain the OD demand for each linetype network, how to formulate the line planning problem integrating the passenger demand (OD demand and loads, deriving from the travel chains), the infrastructure utilization of the different linetypes, and possibly assumptions on the number of passenger transfers for the travel chains. The configuration of timetabling constraints according to the SI and in form of event-activity networks is also described.

2.2 System split and demand allocation

2.2.1 Public transport network and linetype networks

The transportation infrastructure (physical road or track network) is often modeled on a aggregated topology level and can be represented by the *public transportation network* PTN = (V, E) , where V denotes the set of stations and $E \subseteq V \times V$ the set of direct connections, as tracks in a railway network.

Linetypes represent different service or supply types offered by a railroad company. Usually, each linetype is defined by a level of speed and by a stopping pattern, implying that for a given linetype some stations may not be included in the set of stops. Therefore, starting from the physical transportation network, *linetype networks* can be constructed, which are the so-called supply networks or *systems* in this case (Bussieck, 1998).

Linetype networks and of course the railroad network itself, can be modeled using a finite graph $G_X = (V_X ; E_X)$ where X represents a particular linetype (e.g., $X \in \{IC, IR, R\}$, corresponding to InterCity, InterRegional or InterRegio, Regional respectively). The set of nodes $V_X \subset V$ represents the stops of the linetype network (selected from the stations in the PTN) and the set of edges E_X represents the connecting edges between adjacent stops. An edge $e \in E_X$, that is a *linetype-specific edge* (or linetype edge in short), consists in general of a sequence of tracks and stations $v \notin V_X$. G_X may be directed (e.g. networks with one-way tracks) or undirected. In this work we assume that the linetype network is undirected. A *line l* is a path in the public transportation network PTN, served by a train. Since a path on a linetype network is also path in the PTN, a line of a given linetype X can be defined on the linetype network X. It is often

assumed that all lines are served with a common period *Per*, i.e., all departures or arrivals are repeated every *Per* time units. The decision, if a station *v* is included in the stops of a given linetype, is often based on the infrastructure of this station as well as on the volume of traffic at *v*. Generally, linetype networks have a hierarchical arrangement like $V_{IC} \subset V_{IR} \subset V_R$. Depending on the relation between linetypes and the infrastructure, linetype networks can be disjoint. Attributes of the edges $e \in E_X$, as the ride time in minutes, can be expressed by a mapping f : $E_X \rightarrow S$, where S is an appropriate set. For example, $S = \mathbb{Z}_+$ for the ride time mapping f^{RT}. These attributes can vary for edges of different linetypes on the same PTN edge (e.g., different vehicle speeds for different linetypes).
Here a line belongs to exactly one linetype, hence the determination of a line plan for the global (railroad) network can be divided into line planning process steps for each linetype network separately.

2.2.2 System split

The origin-destination passenger demand is usually given in form of a matrix $P \in \mathbb{Z}_+^{n\times n}$ (*n* denotes the number of stations in the transportation network) where the entry $P^{a,b}$ represents the number of passengers traveling from station *a* to station *b* within the given time period (e.g. average hourly demand during weekly working hours). The system split technique, introduced in (Oltrogge, 1994), *splits* the passenger traffic of the complete transportation network over linetype networks by allocating passengers on generated travel chains, defined by a sequence of linetype edges. The technique is based on the criterion that a reasonable journey in the transportation network, especially if starting and ending in small (traffic volume) stations, may start with a sequence of linetype changes to higher linetypes and may terminate with a sequence of changes to lower linetypes (e.g., R — IR — R , or R — IC — IR — R, and not IR — R — IC). In this way journeys can be decomposed and seen as a sequence of *linetype components* (journeys on only one given linetype network), corresponding to a linetype edge or a sequence of them, and multi-linetype travel chains are added to the options for each OD pair. Using utility functions mainly based on the assumption that travelers use the shortest path in each linetype component, it’s then possible to calculate the travel route for each combination and for the linetype-specific edges. The paths, subject to the assumptions above, can be computed with the Floyd-Warshall algorithm (Floyd, 1962; Warshall, 1962). One might as well apply the algorithms for hierarchical shortest path to each sequence of line components.
The utility function proposed by (Oltrogge, 1994), used to select travel chains and allocate the passengers, is based on the ride time, price, level of comfort, and the number of linetype changes. Note that passengers commuting from *a* to *b* can be classified by their trip purpose (e.g., vacation or business trips), leading to different results for the valuation. This framework for line planning is widely accepted by researchers as well as by practitioners (Bussieck, 1998).

2.2.3 Passenger demand for each linetype

After the allocation of the passengers, an aggregation over the travel chains allows to derive the traffic volume over the linetype edges and an OD matrix for each linetype network. The concept followed in this work is that p passengers traveling on a linetype component ab_X (of their travel chain) occupy the linetype network X from the beginning of the component a to its end b. Hence, the p passengers contribute to the traffic load $ld(\mathrm{e})$ of the linetype edges $e \in \mathrm{E}_\mathrm{X}$ defining the component ab_X, and to the entry $P_X^{a,b}$, where P_X is the OD matrix of the linetype network X. For example, let $p \le P^{\text{Luzern, Wolhusen}}$ passengers of the OD pair (Luzern, Wolhusen) use the travel chain r with a linetype change in Malters (details of the example in Section 3):

$$r = \text{Luzern} \overset{R}{\rightarrow} \text{Malters} \overset{IR}{\rightarrow} \text{Wolhusen}$$

where the linetype components and involved linetype edges are

$$\text{Luzern} \overset{R}{\rightarrow} \text{Malters} = (\text{Luzern}, \text{Littau})_\mathrm{R}, (\text{Littau}, \text{Malters})_\mathrm{R}$$

$$\text{Malters} \overset{IR}{\rightarrow} \text{Wolhusen} = (\text{Malters}, \text{Wolhusen})_\mathrm{IR}.$$

Therefore, by defining the travel chain in terms of linetype edges we have

$$r = ((\text{Luzern}, \text{Littau})_\mathrm{R}, (\text{Littau}, \text{Malters})_\mathrm{R}, (\text{Malters}, \text{Wolhusen})_\mathrm{IR}).$$

The p passengers contribute to the OD pair (Luzern, Malters) in the R linetype OD matrix P_R, and to the pair (Malters, Wolhusen) in the IR linetype OD matrix P_{IR}.
The p passengers contribute also to the load on the edges of linetype R (Luzern, Littau)$_\mathrm{R}$, (Littau, Malters)$_\mathrm{R}$, and to the load on the edges of linetype IR (Malters, Wolhusen)$_\mathrm{IR}$.

2.3 Line planning

Given the traffic load of the linetype edges, it is possible to set up a cost minimizing problem to obtain the line plan, where an appropriate frequency (in the same time period of the demand) is assigned to a set of candidate lines $\mathscr{L}$, each defined on linetype edges and on a specific linetype network (a line belongs to a linetype, meeting linetype specifications).
The traffic loads are translated into minimum frequencies based on the capacity of the vehicles. The maximum capacity of the transport network infrastructure can be modeled with maximum frequencies mainly depending on vehicle speeds. In the integer program for solving the classic cost minimizing problem (Schöbel, 2012), the frequency of the candidate lines f_l are the variables:

$$
\begin{aligned}
&\text{(LP-Cost)} \min \sum_{l \in \mathcal{L}} \text{cost}_l \cdot f_l \\
\text{s.t.} \quad & f_e^{\min} \leq \sum_{l \in \mathcal{L}\,:\, e \in l} f_l \leq f_e^{\max} \quad \forall e \in E \\
& f_l \in \mathbb{Z} \quad \forall l \in \mathcal{L}.
\end{aligned} \tag{1}
$$

In order to adapt the line planning problem to the multi-linetype case, by modeling linetype networks and travel chains, the following considerations are made.

The minimum frequency constraints must comply with the demand and are modeled on the linetype edges, while the maximum frequency constraints model the maximum capacity of the infrastructure (e.g. maximum number of reference train runs per hour and direction) and are therefore on the edges of the PTN. In this sense, the lines must be specified with respect to the PTN edges e in equation (1) so that the frequency of the lines occupying a same PTN edge can be summed and an upper bound, representing the maximum capacity of the PTN edge, can be imposed on this sum. Furthermore, it is possible to obtain a line plan aiming at guaranteeing a maximum number of passenger transfers (the effective passenger transfer time is not yet available at this step, according to which the minimum frequencies are estimated) q for each travel chain. In fact, together with the maximum number of linetype changes m, a maximum number of passenger transfers in a linetype component n, i.e. when traveling on a linetype network, can be imposed on assumed paths. The model proposed in (Schöbel and Scholl, 2006) allows to limit the number of passenger transfers, given supply network and its (OD) demand (restriction on the passenger paths defined on the Change&Go-Graph, see (Schiewe et al., 2020), the LinTim documentation). Hence, by including the different linetype networks and the related demand in this model, a maximum number of transfers for each linetype network (so for the linetype components, specified by the OD demand) can be specified. If the maximum is the same for all the linetypes,

$$
\begin{aligned}
q &= \text{max transfers in linetype components} + \text{max linetype changes} \\
&= n(m+1) + m\,,
\end{aligned} \tag{2}
$$

where $(m+1)$ represents the maximum number of linetype components for each travel chain.

2.4 Timetabling problem: travel chains and the service intention

The timetabling problem aims at assigning a departure time and an arrival time to each train run at each stop. Given the set of stops V and the set of train runs T, a timetable consists of two functions $\pi^{arr} : V \times T \to \mathbb{N}$, $\pi^{dep} : V \times T \to \mathbb{N}$ (Michaelis and Schöbel, 2009).

The desired timetable follows the technical and commercial requirements specified by the service intention, the obtained line plan and the travel chains. The service intention (SI) contains all transport services that a railway company would like to offer to the customers, generally over a day (Caimi, 2009), and specifies the conditions to compute a timetable which realizes a given line plan. Each train service is specified, including the line, stopping stations, passenger transfer possibilities, periodicity, and time frame. Timetabling constraints including realizable process times (e.g., driving times, waiting or dwell times, headway times, synchronization intervals), and commercial requirements (e.g. line frequencies and transitions) are described. Therefore, the SI contains customer-relevant information.

As the rail traffic (train routes and their interdependencies) can be modeled as a set of events (departures or arrivals) and activities (e.g., drive, wait, headway, change) between them, the constraints to compute a periodic timetable (here based on the PESP model, see e.g. (Serafini and Ukovich, 1989)) and thus the requirements to implement the service intention, can be modeled with an event-activity network (EAN). A timetable is obtained by assigning times to the events in the EAN modeling the time constraints, specified by the SI. As also shown in (Dollevoet et al., 2018), (Nachtigall, 1998) the EAN is a graph where the events are modeled as vertices and the activities as directed edges.

It is used in public transportation for timetable development and in delay management. An example of representation of an EAN is illustrated in Figure 3. Let PTN = (V, E) be the network of a rail infrastructure and T be a set of train runs. The set of all train runs that stop at station $v \in V$ is denoted by $T(v)$. The event-activity network associated to PTN, $EAN_{PTN} = (H, A)$ consists of the set of events $H = H_{arr} \cup H_{dep}$, and a set of directed edges called activities $A \subset H \times H$. An arrival event (v,t,arr) represents the arrival of a train run $t \in T(v)$ at a station v and a departure event (v,t,dep) represents the departure of train run $t \in T(v)$ at station v. The set of activities includes the following relevant subsets:

- A_{drive} (driving activities) are of type $((v_1,t,dep), (v_2,t,arr))$ for some $(v_1, v_2) \in V$, $t \in T(v_1) \cap T(v_2)$ and represent a train t driving from station v_1 to the next station v_2,
- A_{wait} (waiting activities) are of type $((v,t,arr), (v,t,dep))$ for some $v \in V$, $t \in T(v)$ and represent dwelling activity of train t in station v,
- A_{change} (changing activities) are of type $((v,t_1,arr),(v,t_2,dep))$ for some $v \in V$, $t_1, t_2 \in T(v)$. They do not represent a train's activity, but the possibility for a passenger transfer, so for passengers to change from train t_1 to another train t_2 at station v.

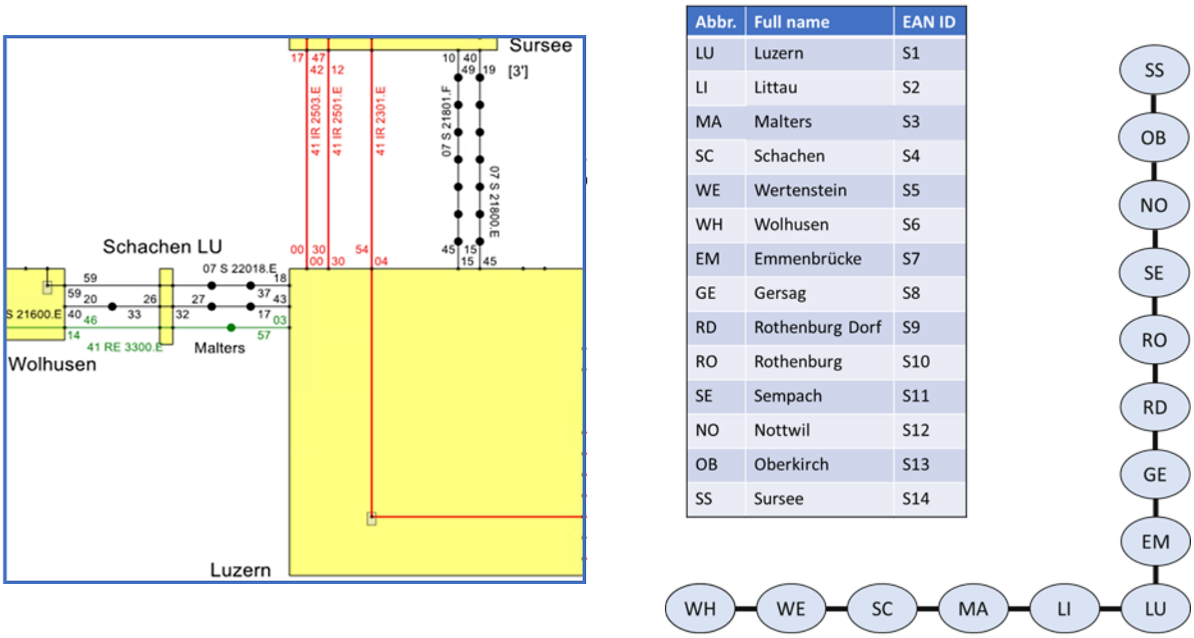
For brevity, we will use drive, wait and change for driving, waiting, changing respectively when referring to the activities. Activities can also represent headways, modeling a minimum time separating two events belonging to two different trains to ensure safe operations, and the train operations between the last event of a train run and the first event of the following one (turn-around activities). A time range complying with the demand allocation step (system split) and with the SI can be specified for the activities (constraints), which can help to find a feasible solution and so a timetable. Furthermore, in this way the duration of the activities according to the obtained timetable may have a longer duration than the required minimum time (specified by the range), thus some buffer time that increases timetable robustness.

The travel chains, defined as a sequence of linetype edges, can imply linetype (network) changes (adjacent edges belonging to different linetypes), possible with passenger transfers modeled as change activities in the EAN. An example is given by the travel chain *r* above, where the linetype edges $(\text{Littau, Malters})_R$, $(\text{Malters, Wolhusen})_{IR}$ are adjacent. Depending on the line plan, a travel chain can imply change activities within a linetype network too, in accordance with the assumptions for the allocation of the demand as mentioned in Section 2.3. In the example of the travel chain *r*, the subsequent linetype edges $(\text{Luzern , Littau})_R$, $(\text{Littau, Malters})_R$ may be covered by different lines and a change activity in Littau would be needed in this case. On the other hand, the transit of passengers using a certain travel chain *r* is specified by the drive activities represented by the corresponding linetype edges. The proposed approach ensures the consistency of the timetable with the assumed travel chains with the configuration of these activities. In fact, a travel chain and its allocation of passengers are ensured by the sequence of drive (and wait) and change activities which make the transit over the linetype edges realizable and by durations of the activities complying with the assumptions made for allocating the passengers. If a timetable satisfies the related constraints, it is also consistent with the travel chain, i.e., the travel chain can be realized as assumed.

The travel chain *r* considered in the previous examples is realized by a sequence of drive activities ((Luzern, t_1, dep) , (Littau, t_1, arr)) , ((Littau, t_2, dep), (Malters, t_2, arr)) , ((Malters, t_3, dep), (Wolhusen, t_3, arr)), with change activities in between whenever subsequent drive activities take place on different trains (e.g., $t_1 \neq t_2$) . Since drive activities also represent the transit of a train over a linetype edge, selecting the drive activities for a travel chain means selecting the trains (so lines and its repetitions if any) on which the travel chain is realized.

3. Experimental results: Luzern area

The proposed approach is used to produce a realistic timetable for the area around the city of Luzern, whose netgraph of the timetable STEP2025, in a version from 2016, and PTN are represented in Figure 1. To illustrate an example on how the assumptions for an OD pair are kept over the timetable planning steps, results in terms of travel chains, allocation of the demand and configuration of the EAN (related part) are also described for the pair Luzern-Wolhusen. Two different directions are considered, i.e. to Sursee and to Wolhusen. On the direction to Sursee, there are 9 stations (Luzern and Sursee included), while on the direction to Wolhusen there are 6 (Luzern and Wolhusen included). The stations are specified in Figure 1.



Abbr.	Full name	EAN ID
LU	Luzern	S1
LI	Littau	S2
MA	Malters	S3
SC	Schachen	S4
WE	Wertenstein	S5
WH	Wolhusen	S6
EM	Emmenbrücke	S7
GE	Gersag	S8
RD	Rothenburg Dorf	S9
RO	Rothenburg	S10
SE	Sempach	S11
NO	Nottwil	S12
OB	Oberkirch	S13
SS	Sursee	S14

Figure 1. On the left, the current timetable plan with the IR, RE, S lines respectively in red, green and black. The points on the lines represent stops. On the right, the PTN with a reference table.

In order to simplify the example, we define two linetypes, the Regional (R), stopping at all the stations in the PTN, and the InterRegional (IR). Therefore, the line RE 3300 (the line between Luzern and Wolhusen in green, Figure 1) is ignored.

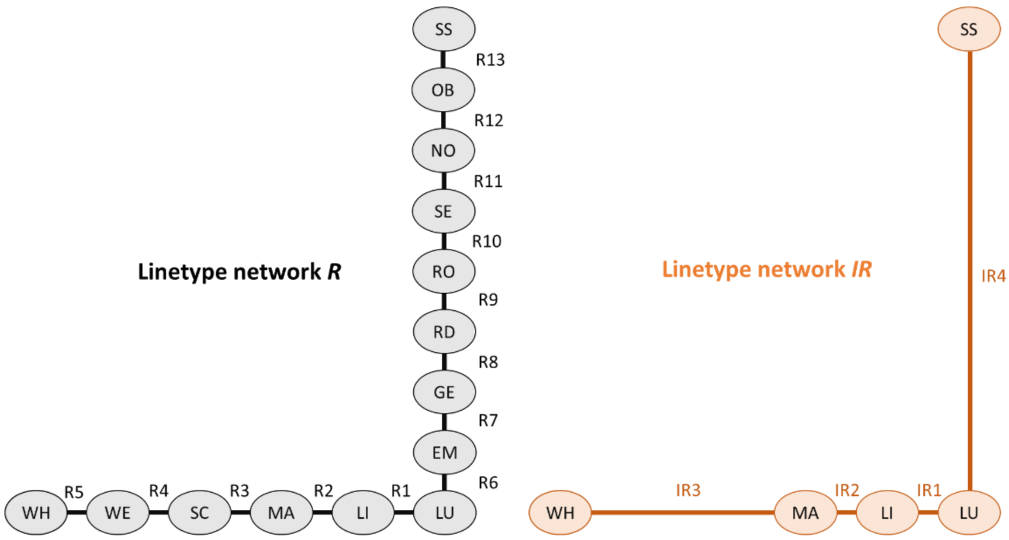


Figure 2. The considered linetype networks

The IR linetype network includes Luzern, Sursee (direction to Sursee), and Littau, Malters, Wolhusen (direction to Wolhusen).

In this example scenario, the OD pair Luzern-Wolhusen has an hourly demand of 60 passengers, for which the system split technique generated the travel chains and the related allocation. In Table 1, the possible travel chains are shown together with the corresponding estimated travel times. In our example, the utility function to evaluate the travel chains and to allocate the passengers corresponds to the estimated travel time including the passenger transfers due to linetype changes. However, as mentioned in Section 2.2.2, it's possible to calibrate the parameters to consider also other aspects than travel time, as level of comfort or price. It can be noticed how the estimated travel time affects the allocation of the passengers. The chain (i) represents the fastest alternative and has more passengers than the others; for the chains (v), (vii) and (viii), the more is the travel time, the less are the assigned passengers.

Table 1. Travel chains for the OD pair Luzern-Wolhusen

	Travel chain	Est. time (min)	Passengers
i.	**IR1, IR2, IR3**	19.7	34
ii.	**IR1, IR2, R3, R4, R5**	27.3	0
iii.	**IR1, R2, IR3**	26.2	0
iv.	**IR1, R2, R3, R4, R5**	27.8	0
v.	**R1, IR2, IR3**	23.2	12
vi.	**R1, IR2, R3, R4, R5**	30.8	0
vii.	**R1, R2, IR3**	23.7	10
viii.	**R1, R2, R3, R4, R5**	25.3	4

The resulting travel time threshold to consider a chain in the allocation is ca. 26.9 min., which excluded the chains (ii), (iv), (vi). The chain (iii) has been discarded since travel chains including a linetype component enclosed by higher linetype components (here IR—R—IR) are not allowed according to the system split technique.

The considered set of candidate lines, specified on the linetype networks, consists in a couple of (symmetrical) lines, one for each direction and linetype (lines 1(IR), 2(R) for the direction Luzern-Wolhusen and lines 3(IR), 4(R) for Luzern-Sursee). The integer program for the classic cost minimizing model for line planning described in Section 2.3 assigned a hourly frequency (as the period of the OD demand is an hour) of 2 to each candidate line, satisfying the traffic load over the linetype edges with a specified vehicle capacity of 300 passengers. For instance, the aggregation over the travel chains (so also over the travel chains for the example of OD pair Luzern-Wolhusen) returned a load of 515 passengers on the Regional (R) linetype edge Littau-Malters (direction Wolhusen), and the minimum frequency on this edge with the given vehicle capacity is 2 ($2*300 = 600 \geq 515 \geq 1*300$) .

The EAN for each linetype can also be obtained in the LinTim environment. Hence, the next step to integrate the multi-linetype travel chains in the activity constraints is to include the required change activities. In the example of the OD pair Luzern-Wolhusen, r = (vii) is a possible travel chain:

$$r = (\text{Luzern , Littau})_R \text{ , (Littau, Malters)}_R \text{ , (Malters, Wolhusen)}_{IR}$$
$$= \quad R1 \quad , \quad R2 \quad , \quad IR3 .$$

A change activity between different linetypes is required in Malters, from a Regional (R) to an InterRegional (IR) train. According to the line plan, it could be possible that even if there are Regional lines on both (Luzern , Littau)$_R$, (Littau, Malters)$_R$, there is no Regional line traveling on these linetype edges consecutively. In this case a change activity is also required in Littau. The sequence of activities on which the chain r can be realized is illustrated in the representation of the EAN in Figure 3. The computed event times represent the final timetable, and since they

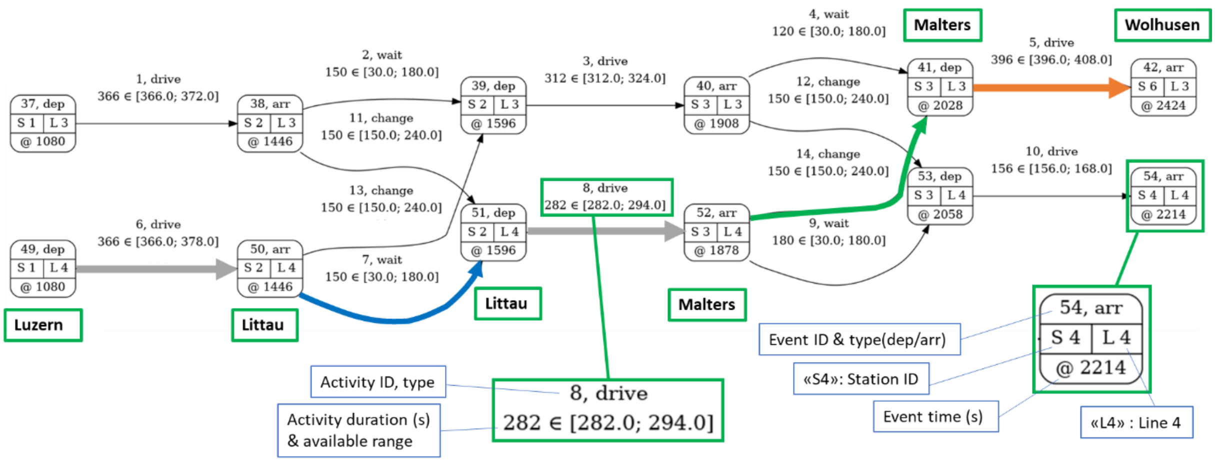


Figure 3. Part of the EAN showing the travel chain r = R1, R2, IR3 for the OD Luzern-Wolhusen (bold arrows, the R and IR lineypes are respectively in grey and orange)

satisfy the constraints they are consistent with the travel chains, i.e. the travel chains are realized and under the same assumptions made for the allocation (system split).

4. Conclusions and future directions

In this work we proposed an approach to generate multi-linetype timetables by performing the network design, line planning and timetabling steps under the same assumptions. First, the supply is determined (before there is a line plan) via the use of one or more travel chains, defined on one or more linetype networks, for each origin-destination travel demand. This implies the possibility of more route options. The assumptions on the supply are kept in the subsequent line planning and timetabling steps, where the line plans of the different linetypes are coordinated via the timetabling constraints, following the SI and expressed in form of EAN.
As a consequence, the transport service meets a level of service quality defined a priori, and the finally obtained timetable doesn't require adjustments to satisfy assumptions on travel chains, also in the multi-linetype case.

The procedure to generate timetables has been extended by integrating the system split technique, the computation of the OD demand for each linetype network, modeling the line planning problem with the considered linetype networks, and configuring the timetable constraints to comply with the initially determined travel chains. The approach has been tested on a realistic scenario around the city of Luzern, and examples to describe the application are provided. There are many directions to extend this work. The effective travel time for a travel chain after computing the timetable may differ from the value estimated at the beginning (system split), since the time constraint for an activity can be specified with a range and not a single value. A revaluation of the travel chains may therefore alter the allocation. Hence, desirable next steps will include criteria under which the allocation is compatible with the valid time ranges for the activities. Another required addition to follow the proposed approach consists in modeling all the change activities specified by the travel chains in the EAN. Other examples are the use of the approach in the operational context of timetable replanning, where the demand and the infrastructure capacity (see PTN and frequency boundaries in line planning, e.g. in the integer program (1)) may differ from the planned conditions, and the analysis of the computational performance on bigger scenarios (more stations, tracks, linetypes).

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