Infrastructure Update According to Schedule? ⋆

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Abstract

Integrated fixed-interval timetables (IFIT) are a very simple class of periodic timetables. At selected stations, the trains of all lines meet at a pre-defined time. If the running times between the selected stations allow such a timetable, an IFIT can indeed represent an attractive service. But what happens, when the running times are not appropriate?

In practice, running times are often adapted to match with the requirements of such an IFIT system — often involving a very expensive upgrade of the infrastructure. In addition to the cost of the investments, further drawbacks, such as a very inflexible system showing a highly unbalanced utilization, are a consequence. Moreover, midterm maintenance can only be responded in a limited way. Finally, in some way, gradual improvements to the system are even obstructed.

Instead of such *infrastructure upgrades according to schedule*, we propose to apply a flexible planning software, which computes mathematically optimized periodic timetables, that meet the individual requirements of every planning period. This is the only adequate approach to implement the concept of the managing director of DB Personenverkehr GmbH: The *hardware* of a rail system are infrastructure and rolling stock, of which the timetable as flexible *software* has to make most efficient use (ETR 03/2004).

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1 Introduction

Network and timetable are the core of every service concept in public transport. From the customers' point of view, these are crucial for the competitiveness compared to other means of transport. Short distances to the stops, high frequencies of service, and short travel times are particularly attractive.

On the one hand, the quality of the network does immediately affect travel times. On the other hand — in particular if a journey involves changeovers — the timetable defines the slack times within the system. Obviously, the amount of unavoidable total changeover waiting time in a network can be interpreted as a function of the running times a certain infrastructure makes possible. Hence, an integrated planning of these two tasks would be desirable. However, their functional dependency is highly complex. In particular, for the near future there is no perspective that methods of operations research will be able to solve such integrated problems for relevent networks. Due to the different planning horizons for infrastructure and operations, one may even ask whether such an integration is really what companies should aim at.

Nevertheless, in practice a certain trend towards an integrated planning emerged. The high complexity is eliminated by only considering those infrastructure states which enable integrated fixed-interval timetables (IFIT), which in turn are a very special subset of general periodic timetables.

We will present the possible benefits of such an IFIT driven integrated planning, but we will also point at some major risks of this strategy. In turn, we shortly describe the power of today's state-of-the-art methods for periodic timetable optimization. When applied to practice, these might also provide considerable reductions of travel times — without requiring any (expensive) infrastructure upgrade.

This paper is organized as follows. In Section 2 we describe the planning process in railway traffic and specify the interfaces, which timetabling shares with other tasks. In Section 3 we present the concept of so-called integrated fixed-interval timetables. Sections 4 and 5 illustrate two different strategies to face up to an infrastructure, which is insufficient for the requirements integrated fixed-interval timetables impose: Either upgrade the infrastructure, or make clever use of the existing one by applying mathematical optimization.

2 Timetabling

Traditionally, planning the service and operation of railway traffic is performed hierarchically. First, the step of network planning is performed, in which decisions on infrastructure are taken. Then, in line planning the service lines are defined, together with their frequencies. Next, a timetable has to be constructed. Finally, on the level of operations, vehicle scheduling and crew scheduling are effected.

During the last decade, in the field of vehicle and crew scheduling, methods of operations research did find their way into praxis. There are even some recent developments for integrating these two tasks. Other tasks are the objective of integration, too: Network planning and line planning[1], and timetabling together with vehicle scheduling and some aspects of line planning[4].

In practice, an even broader integration is currently under way: Oftentimes, before implementing an integrated fixed-interval timetable, even the infrastructure is redesigned in order to form an attractive service together with a timetable, see also Section 4.

Given the increasing separation between infrastructure and operation, we shortly give our assumptions on knowledge and aims of the different players for that such an integrated planning will still be possible in future. We assume that the infrastructure company, or authority resp., sets up the final timetable and is responsible for infrastructure update. The infrastructure company also has an idea of the future demand of passengers, and information on the future service concepts of the railway operators. These want to offer an attractive service to passengers at payable (operational) costs. In particular, they consider fully regular periodic timetables to be an outstanding attractive type of service, as well as operationally well-manageable.

Let us now explore in more detail, what timetabling is all about. This task subdivides into several minor steps. First, several homogeneous traffic slices might be defined (peak-hours, night traffic etc.). Second, for each such slice a periodic timetable has to be computed. Third, transitions between the periodic timetables for the different slices as well as special rules at the beginning and at the end of the day must be found. Last, special single trips (e.g. for sport events) are introduced. This article will only cover the second step, whose result is in fact the core of every timetable.

In railway traffic, there are often defined at most two traffic slices, where outside rush-hours, occasionally every second trip is just omitted. Hence, we may think of the whole timetable as one single system. As during off-peak hours usually a one (or two) hourly service is present, the core of the timetable can be described by one so-called basic hourly pattern (BUP), which is an abstraction of precise times of the day. For instance, a departure at "minute 26" represents a whole series of departures: ..., 10:26, 11:26, 12:26, ...

Throughout this article, for every line and any pair of adjacent stations along its route, we assume identical running times for the two directions of that line. Moreover, for the two directions of a line we assume the stopping times at stations to differ only negligibly. Then, we have the following property for periodic timetables.

Fact 1 *For every traffic line, the trains of its two opposite directions meet twice within the period time T.*

Definition 2 *A periodic timetable is called* symmetric *(with* symmetry axis *zero), if and only if for every line, its two directions always meet at time* 0 *— and, hence, at time* $\frac{T}{2}$*.*

Trivially, other symmetry axes $s \in [0, \frac{T}{2})$ are possible. Nevertheless, large parts of the railway timetables of Germany and Switzerland, for example, are symmetric with an axis close to zero. For structural properties of symmetric timetables, we refer to Liebchen[3].

3 Integrated Fixed-Interval Timetables

Definition 3 *If in a symmetric timetable all lines meet at the same station at time zero ($\frac{T}{2}$), this station is called a* zero hub (half hub) *of an* Integrated Fixed-Interval Timetable (IFIT)*.*

Since the concept of integrated fixed-interval timetables is extremely simple, planning the timetable becomes an easy task. In particular, interfaces to both, international and regional traffic, become well controllable. One may ask, whether additional requirements on periodic timetables such as symmetry and zero hubs just emerged in order to simplify manual planning?

But such an argumentation would be much too simple as well. Integrated fixed-interval timetables can indeed form an attractive offer to customers. In particular, within the zero hubs, no waiting times for changeovers arise, cf. Figure 1. Further, the departure times at zero hubs can easily be kept in mind by customers. Finally, IFIT inherit the structural properties of symmetric timetables.

But an IFIT is only that easy, because it is in fact a very restrictive concept. For that infrastructure enables more than one hub, the running times between any two hub candidate stations must be slightly less than integer multiples of $\frac{T}{2}$.

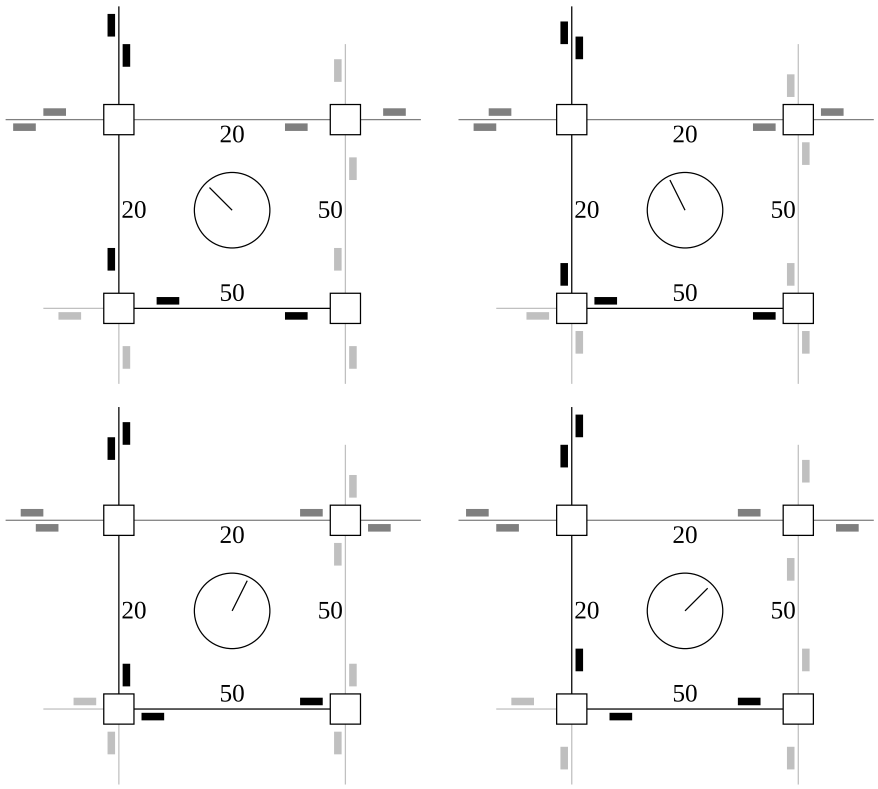

Fig. 1. Integrated fixed-interval timetable

Although this is already a very strong requirement on the interaction between infrastructure and rolling stock, it is not even sufficient for a railway network to enable several hubs. Consider the graph formed by the network's stations and tracks. Assume, we have a triangle of three stations with running times $\frac{T}{2} - \epsilon$ between any two stations. In this case, only two of the three stations can be installed as hubs, although the criterion of the running times is not violated.

The answer is that the graph has to be bipartite. More precisely, for a track of running time $k \cdot \frac{T}{2} - \epsilon$, $k \in \mathbb{Z}$, we introduce $k-1$ artificial nodes subdividing the edge modeling that track, and require the resulting graph to be bipartite, i.e. not to contain a cycle with an odd number of (artificial) edges. Then, the nodes in one part of the bipartition are precisely the zero hubs, the other nodes are the half-hubs. We call a system of hubs *compatible* to a given infrastructure, if and only if the above graph is bipartite.

Now that we are aware of the strong requirements the IFIT concept poses to the infrastructure, we can formulate the crucial question for the concept of integrated fixed-interval timetables:

What shall we do, if infrastructure does *not* meet these requirements?

Given the fact that it would be unacceptable for passengers to increase an existing running time r to $\left\lceil \frac{r}{\left(\frac{T}{2}\right)} \right\rceil \frac{T}{2}$, we have, roughly spoken, two major alternatives: Either, we adapt the concept for the timetable — and thus offer less hubs to customers — or we adapt the infrastructure, i.e. reduce the running time down to $\left\lfloor \frac{r}{\left(\frac{T}{2}\right)} \right\rfloor \frac{T}{2}$, cf. Figure 2. In the following two sections, we discuss these two alternatives. In particular, Section 5 presents a powerful mathematical model, with which we are able to construct optimal periodic timetables for a fixed given infrastructure.

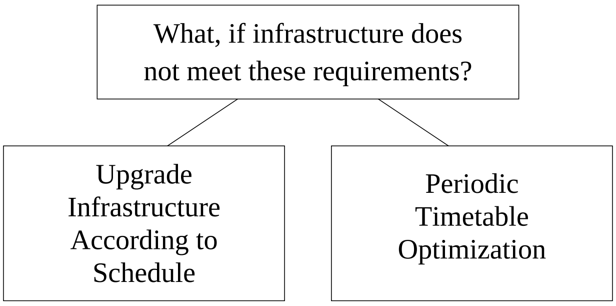

Fig. 2. Two major alternatives, if infrastructure does not meet IFIT requirements

4 Infrastructure Update According to Schedule

One may ask, whether it is really an option in practice to guide long-term investments into infrastructure by the needs of a specific concept of a timetable. Indeed, it is.

The regional government of Schleswig-Holstein, being financially responsible for the public transport in its region, replies to the written request of a member of parliament:

> Our planning envisages to reduce the running time on the track Kiel-Lübeck from 73 minutes down to less than one hour to integrate it into the integrated fixed-interval timetable.

Deutsche Bahn proceeds the same way in Saxony. The running time between Leipzig and Chemnitz will be reduced from 85 minutes down to approximately 50 minutes. For the refurbishment of the tracks between Leipzig, Döbeln, and Meißen, Deutsche Bahn AG gives the following motivation:

After completion of the refurbishment measurements, the running times Leipzig-Döbeln and Döbeln-Meißen will be reduced to significantly less than one hour, in order to guarantee their integration into the Sachsen-Takt (integrated fixed-interval timetable for Saxony).

But this is not only a German strategy. On December 6th, 1987, the Swiss people agreed in a referendum to adapt the infrastructure of Swiss Federal Railways (SBB) to the requests of a specific IFIT concept:

The new line construction Mattstetten - Rothrist is the core part of Rail 2000. As from 12 December 2004, the Inter-City trains connect Bern with Zurich at a speed of 200 km/h. On this line, no station and no turnout will hinder their swift run. The journey from Bern to Zurich will take 56 minutes only (currently 72 minutes).

On December 12th, 2004, the first phase of Rail 2000 will be ready for operation. Then, most running times will satisfy the $k \cdot \frac{T}{2} - \epsilon$ property, as is illustrated in Figure 3. And since the project Rail 2000 of SBB is currently

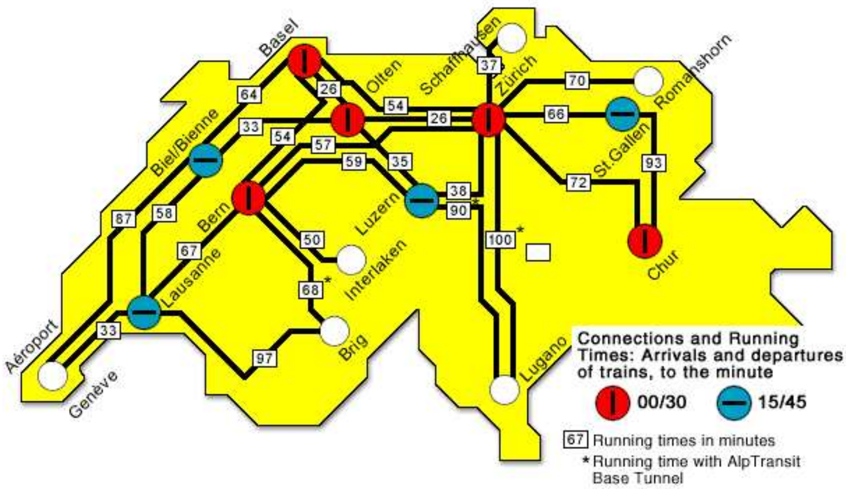

Fig. 3. Running times in the Rail 2000 system (Swiss Federal Railways[12])

establishing a half-hour frequency on most routes, half hubs are served at minutes 15 and 45:

In the first phase of Rail 2000, the stations of Basel, Bern, Olten, Zurich and Chur serve as hubs each hour or half-hour. In the stations of Lausanne, Biel, Lucerne and St.Gallen, the trains will meet each time at a quarter to and a quarter past the hour.

Despite their dissemination, integrated fixed-interval timetables have some relevant drawbacks. As the above examples illustrate, oftentimes an IFIT can only be established after expensive long-term investments into infrastructure upgrade. It is much likely that the structure of hubs is kept fixed for the economic life time of the investments. Hence, in some way, the service concept becomes *inflexible*, e.g. against track refurbishment measures or slightly faster trains. There will be no substantial incentive to reduce the current running time of 54 minutes between the two zero hubs Basel and Zurich by, say, only five minutes. Improvements that would fit into such a system must be of much bigger dimension. Hence, gradual improvements tend to be obstructed, c.f. Heese[2] discussing the line Stuttgart-Ulm:

> A speed-up by another 10 to 15 minutes is counterproductive for the Integrated Fixed Interval Timetable.

Let us provide a more detailed — though hypothetical — example. Assume SBB would have adapted its infrastructure already by 1990 such that, together with the rolling stock available at that time, a specific IFIT concept became operable. Recall that the tiling technology for railway vehicles has been still under development at that time. Let us assume that the reductions in running time, which tiling technology is able to realize, range from five to ten minutes between any two hubs, cf. Figure 4. Would there have been a sufficiently

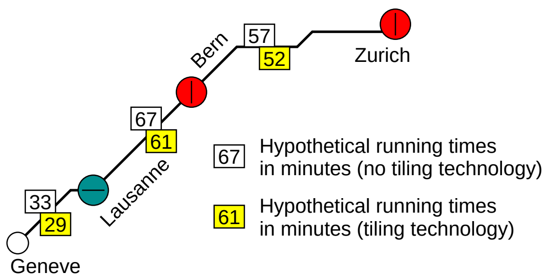

Fig. 4. Hypothetical running times Zurich-Genève with and without tiling technology available

strong motivation in, say, 1993 to order the new faster trains? Probably not, which would have resulted in a freeze of the running time between Zurich and Genève, being roughly twenty minutes longer than innovative technology might have achieved at that time.

But also for daily operation, the degree of inflexibility becomes very obvious when perceiving the fact that IFIT requirements are *equivalent* to have single tracks between any two zero- or half-hubs[9]. Further, given the huge number of very tight connections within the hubs, delays tend to spread easily. Perhaps, an IFIT even tends to induce delays, because stations are the major source for delays and hubs show an unbalanced workload with few but very intense peaks.

To summarize the properties of integrated fixed-interval timetables, we first want to point out that they are extremely simple and can form an attractive service. Nevertheless, the (long-term) drawbacks of expensive infrastructure upgrades according to scheduling requirements, in combination with only a poor degree of flexibility, must absolutely be taken into account. In fact, zero hubs make most sense, if the candidate station has

- a balanced passenger flow instead of only few dominating connections,
- many platforms available having only short walking distances between them, or
- many lines ending at the station, so that the ending trains move to the depot in order to no longer block a platform.

Additionally, an infrastructure upgrade will be out of question, if its necessity for the IFIT coincides with a large number of direct travelers on the track.

5 Periodic Timetable Optimization

Let us now investigate the case in that current infrastructure does not allow a satisfactory number of hubs, and upgrades of infrastructure are not a feasible option. Still, the infrastructure company (authority) has to set up a timetable, which is attractive to the passengers, and thus to the railway operators.

These are precisely the basic conditions for mathematical optimization. More precisely, in periodic timetable optimization, we are given a cycle time T and a line-plan with

- *fixed* running times,
- stopping times,
- changeover activities,
- turnover times, and
- infrastructure information (headways, singletracks, ...).

Then, we have to find arrival and departure times π within the abstract basic interval $[0, T)$ for every line at every station, such that operational constraints are respected and that an attractive, but affordable offer can be established.

Paolo Serafini and Walter Ukovich[14] introduced the Periodic Event Scheduling Problem (PESP) to model the above task. In it, we are given a period time T and a set V of events, where an event models either the arrival or the departure of a directed traffic line at a certain station. Furthermore, we are given a set of constraints A. Every constraint $a = (i, j)$ relates a pair of events i, j by a lower bound ℓ_a and an upper bound u_a.

A solution of a PESP instance is a node assignment $\pi : V \mapsto [0, T)$ that satisfies

$$(\pi_j - \pi_i - \ell_a) \bmod T \leq u_a - \ell_a, \; \forall\, a = (i,j) \in A,$$

or $\pi_j - \pi_i \in [\ell_a, u_a]_T$ for short. Additionally, in order to penalize undesired waiting times, we allow a linear objective function to be defined for every arc.

With this model we are able to formulate almost any of the practical requirements that arise in periodic timetabling[4]:

- Running and stopping activities
- changeovers
- amount of rolling stock
- minimal headways
- single tracks
- crossings
- train coupling/train sharing
- bundling of lines
- fixed events
- zero hubs
- ...

In Figure 5, we briefly illustrate how running, stopping, and changeover activities are modeled within the PESP. Notice that within the PESP model, we may even define stations to become hubs. This can be done very easily by just requiring that $\pi_j - \pi_i \in [\ell_{ij}, u_{ij}]_T$ for every pair of arrival event i and departure event j. Here, ℓ_{ij} denotes the minimal changeover time and u_{ij} is a bound on the maximal changeover time, where 10 minutes seem to be reasonable for an hourly operated system. Let us, however, mention that a system of constraints can easily become overdetermined, in particular if one forces incompatible stations to become hubs. But even when not introducing constraints that would ensure a station to become a hub, this station may become a hub in an optimized timetable, when its connections are sufficiently important.

There are various techniques for solving PESP instances. Without an objective function given, a backtracking scheme and constraint programming were proposed ([14,13]). For minimizing a linear objective function, there has been published a variety of techniques in order to make the resulting mixed integer linear programs (MIP) computationally tractable (e.g. [7,10,5]). Finally, a genetic algorithm approach has been proposed as well ([8]).

In a recent computational study for minimizing a linear objective function over the feasible region of a PESP instance ([6]), the genetic algorithm turned out to beat the reputable commercial MIP solver CPLEX©, being run at

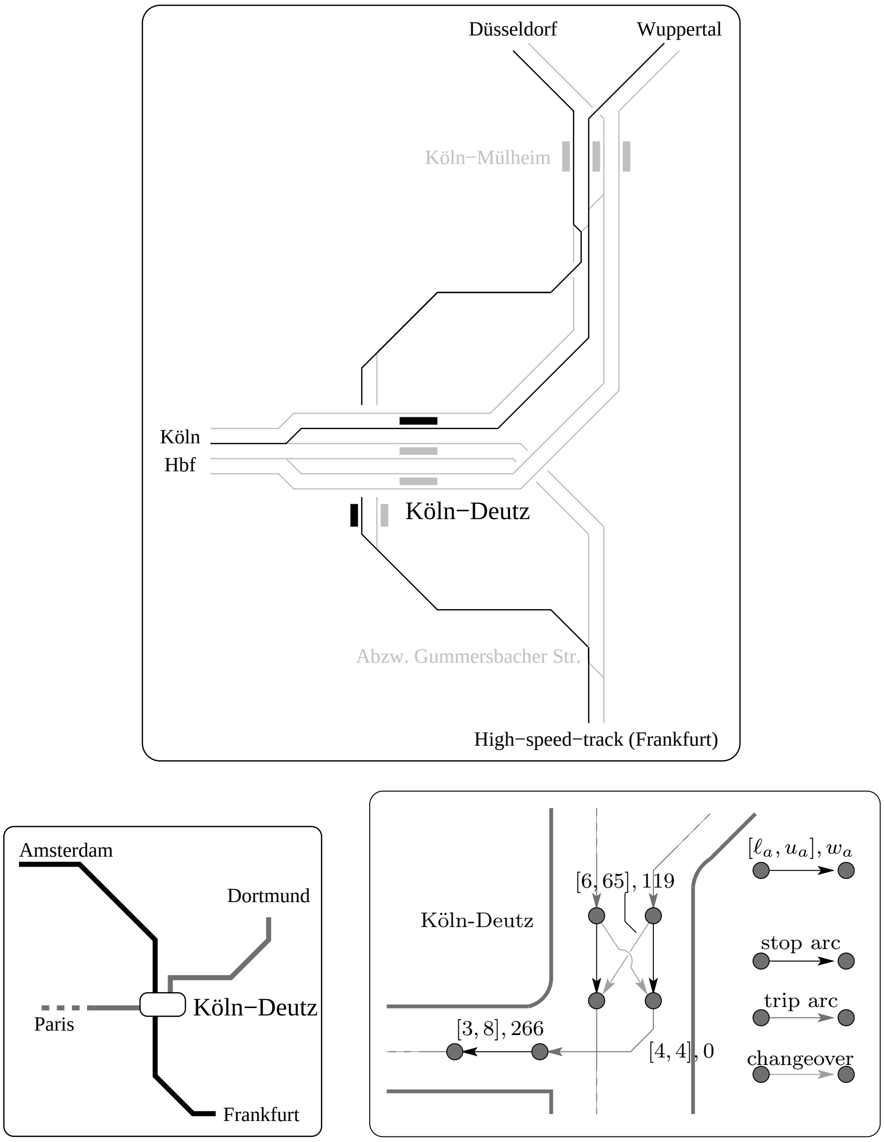

Fig. 5. Modeling running, stopping, and changeover activities

its default setting. In turn, there are parameter settings known that let this MIP solver explore better solutions than the genetic algorithm, within a given timelimit.

Fortunately, the above considerations are no longer only of theoretical nature. Today, the available optimization techniques are able to solve relevant real-world problems of up to 20 or 30 lines. More specifically, both Dutch and German railways currently use mathematical software in their strategy departments. Even closer to realization, for a highly connected public mass transit network with more than one million daily passengers, a timetable which is based on a concept computed by the group "Combinatorial Optimization and Graph Algorithms" at TU Berlin is going to be implemented by December 2004.

Summarizing, for a fixed infrastructure, there are optimization techniques available to compute an optimal periodic timetable. Altogether, we are able to flexibly construct a timetable, optimized for the specific needs of the period to plan.

6 Conclusions

We have described the concept of integrated fixed-interval timetables, which are a subclass of periodic timetables. As they impose very strict requirements on the underlying infrastructure, there are many examples available in which the implementation of an IFIT was preceeded by major infrastructure upgrades.

Since there are also some relevant drawbacks of the IFIT concept, e.g. a lack of flexibility, and often important investment costs, we have pointed out that an infrastructure update is not the only way to respond to IFIT requirements not conforming with the existing infrastructure. Rather, operations research provides techniques to create timetables that are tailor-made for any particular planning horizon. Maybe, this is the flexibility that the managing director of Deutsche Bahn AG's passenger traffic is aiming at:

> Infrastructure and rolling stock are the *hardware* of railways, designed for a long service life. In contrast, the timetable is the *software*, which can adapt more quickly to market changes. Here are challenges and chances to improve the position of railways.
>
> "Fahrzeuge und feste Anlagen sind die Hardware der Eisenbahn, ausgelegt auf (...) lange Lebensdauer. Im Gegensatz dazu bildet der Fahrplan (...) die Software, die sich rascher und kurzfristiger auf Veränderungen des Marktes einstellen können. Hier bestehen Chancen und Herausforderungen, die Stellung der Bahn zu verbessern."
>
> Dr. Karl-Friedrich Rausch, Vorstand Personenverkehr, Deutsche Bahn AG
> Eisenbahntechnische Rundschau (ETR) 3/2004 [11]

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