OptiTakt – A tool for developing and evaluating periodic timetables

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Abstract

In recent years many European transport organisations have introduced and successfully operated *Integrated Periodic Timetables (IPT, also: "synchronised timetables")* in order to improve the travel quality and speed on public transport networks. This can be done by optimising the departure and arrival times of transport media (trains, buses etc…) in such a way that the loss times in a network (e.g. resulting from waiting, using slow trains or from detours) are minimised.

In this article, we present OptiTakt, a tool for the timetable planner which was developed in a Ph. D. project at the University of Marburg and which has successfully been applied in several timetable development and improvement projects. The focus of this tool is on building timetables under realistic conditions, interactive timetabling, using multiple views on schedules and on simulation for infrastructure planning.

An absolutely optimal IPT is only possible under certain infrastructure conditions, which normally cannot be expected for already existing networks. Thus the construction of an optimal IPT is both a computational and an infrastructural optimisation problem: From the mathematical point of view, heuristic algorithms are required for its solution whenever networks of realistic size are to be treated. However, similar algorithms can also be used to figure out the most effective improvements of the technical railway infrastructure in order to achieve optimal connections for the majority of travellers within the network.

Keywords

Integrated Periodic Timetables, interactive timetabling, railway infrastructure planning, OptiTakt tool

1   Periodic timetables and the IPT optimisation problem

The attractiveness of a passenger transport network for potential users does not only depend on the speed and comfort of its trains, buses or other transport means. At least as important are the frequency of service and the quality of change connections. In recent years many European Railway organisations have introduced and successfully operated *Integrated Periodic Timetables (IPT, also: "synchronised timetables"), i.e.* timetables with a fixed period of repeated service on most or parts of their network lines and have

tried to optimise the connections between these lines. In the following sections, we shall present our *OptiTakt* tool, which has been designed to support the development, evaluation and comparison of IPTs.

Assume a network of railway lines is represented as a graph - taking all relevant entry, exit and change stations (the *"nodes"*) as vertices and all direct physical connections between these as edges. Sequences of connected edges may be defined as *lines*, i.e. pathways which are used by through trains. Intermediate stations on edges (with no branches) are admitted but of marginal relevance for the problems discussed here. Assume further a set of railway users – called *travellers* – undertaking *trips* within the network each of which is defined by two nodes, an *entry point* and an *exit point*. Lines are classified according to their kind (and priority) of trains, e.g. distinguishing *inter-city (IC)*, *inter-regional (IR), regional express (RE)* and *regular regional (RR)* lines. For each line, a *minimum travel time* on each of its edges and *minimal stop* and *change times* are defined for all nodes of the network.

A *timetable* is defined by a set of lines and all departure and arrival times for all their adjacent nodes. A timetable is called *periodic* if each line offers regular train services running in a certain period of time called the schedule *period*. Mostly, periods of 30, 60 or 120 minutes are defined for mnemonic reasons. We call a periodic timetable *integrated* if the periodic services are synchronised in such a way that good change conditions at (almost) all nodes are given. For systematic reasons, we further focus on *symmetric* timetables, i.e. if a train running every 60 minutes arrives at minute x at station A, its opposite train will depart from A at minute 60-x.

Taking all (actual or potential) user trips on a defined network in a certain time interval (e.g. one day), we look for an optimised schedule, i.e. one providing the minimal overall travelling time for all these trips. We call the problem to find such an optimal schedule the **IPT optimisation problem.** Not surprisingly, this problem is NP-hard [2] and – as a consequence – good heuristic algorithms are required in order to find good solutions for networks of realistic size (comprising, say, 30, 50 or more nodes).

2   Alternative approaches

Domschke referred to a problem similar to the IPT optimisation problem as a Quasi-Semi-Assignment problem (QSAP) which is a relaxation of the Quadratic Assignment problem and applied several heuristics to find reasonably good solutions [1]. In his approach predefined routes were assumed and change locations were fixed in advance. The OptiTakt model is more flexible in this point since the route between two stations is not predefined but always determined depending on the timetable. Later, other formulations of the IPT were published. We mention the non-deterministic approach used by Kolonko and his team at the Technical University of Clausthal-Zellerfeld. They constructed a program called 'HiTT' which uses genetic algorithms to find optimal integrated periodic schedules. Randomly generated schedules are evaluated concerning the transfer time, the construction costs, the number of trains and the robustness. While worse schedules are filtered out, the better ones are modified and recombined until so-called Pareto-optimal schedules are achieved. Tests of this optimization system with simplified networks show that this approach is interesting but not yet fully developed [8].

Liebchen et al. describe a comparison of five different solution approaches for the task of constructing periodic timetables for public transportation companies. The approaches are based on the Periodic Event Scheduling Problem (PESP) which was introduced in 1989 by Serafini and Ukovich extending it with an additional objective function [9]. The Periodic Event Scheduling Problem is to find a feasible solution for a set of periodical interval constraints, which are formulated for the arrival and departure events of every line. In another paper, Liebchen discusses the significance of symmetry in periodic timetables. It turns out that symmetry does not always lead to optimal solutions, notably on single track networks or sections.

While all these approaches (and similar ones) focus on the mathematical problem to find optimal IPT solutions, the OptiTakt tool (at least in its kernel version) concentrates on the practical aspects of supporting the timetable planner at his or her work. For example, symmetry is presupposed simply for practical reasons: It is preferred in most existing IPTs for its simplicity and fitness to memorize and it considerably enhances the efficiency of our tool. On the other hand, the tool encourages interactive work and is very flexible on the network structure. For example, it allows re-combination of lines and changes of travel times in order to support the flexible generation of variants and simulation of infrastructure improvements.

3 The OptiTakt approach

3.1 Key concepts and ratios

OptiTakt works with two graph representations of the considered network. The first is close to the real railway network: It contains vertices that represent stations and edges that represent tracks. Each edge carries a set of labels – one label for every line that runs on it. Lines and connections are paths of labelled edges i.e. sequences of tracks used by particular trains. While lines are user-defined (each edge of the path has the same label), connections are determined by OptiTakt (here of course the labels may differ from edge to edge). This is accomplished by a transformation of that graph adding particular edges for multiple uses of tracks and for connection relations. This will be discussed in detail below.

Taking the minimal travel times on the edges (for all kinds of trains) and always the (theoretically) minimal change and stop times at the nodes, an N x N-matrix (the so-called "*ideal travel matrix*") of minimal travel times between all node pairs can be generated. On the other hand, for each given timetable, the actual travel times for all node pairs can be calculated to populate the *actual travel matrix*. Normally, actual travel times exceed the ideal travel time for several reasons. Primary reasons are: spending excess waiting time at change or stop stations, taking a slower train than the fastest one, taking a route other than the shortest possible path. For each node pair the difference between the actual and the ideal time is called the *loss time*.

A given timetable (a setting of all arrival and departure times throughout the schedule) can be evaluated by various calculations and resulting scores. One important score is the *total loss time* (taken over all node pairs). If this score is minimal this is an indicator for good timetable quality. Node pairs can be weighted by the number of (counted or expected) travellers if such data are available. This way, *weighted loss times* and the *total weighted loss time* are calculated as another key quality score.

Let V be the set of nodes, $\delta_{v,v'}$ the loss time and $w_{v,v'}$ the weight between any two nodes v and v' from V. Then we get the following formal definitions:

$$TLT = \sum_{v,v' \in V} \delta_{v,v'}$$

Total Loss Time

$$TWLT = \sum_{v,v' \in V} w_{v,v'} \delta_{v,v'}$$

Total Weighted Loss Time

The IPT optimisation problem can then be formulated: For a given traffic network and a given structure of lines find a timetable that minimizes the values for TLT and/or TWLT.

The original graph structure given by the nodes and the connecting tracks is transformed into the so called *period time graph*. (cf. fig. 1). Here all arrival and departure events of each train are represented by a particular node. The set of edges basically consists of the original edges (one edge for every line that travels on that track) plus additional *"auxiliary"* edges connecting each arrival node with each departure node of a given station. Edges are weighted according to the travel time, stop time or waiting time respectively.
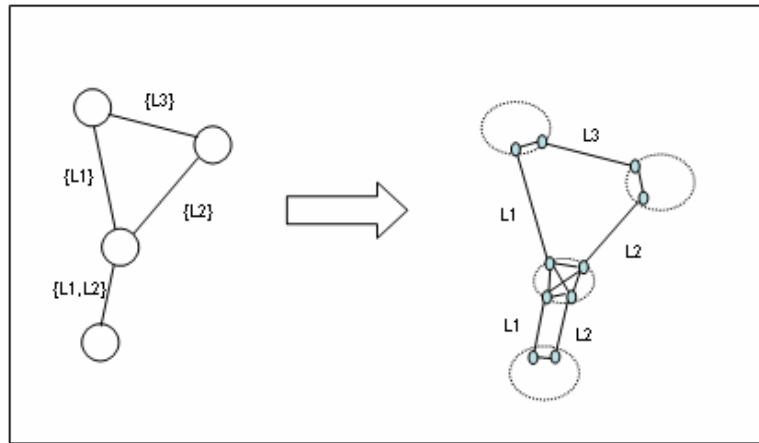

Fig. 1: Period time graph transformation

In this graph ideal and actual times can be calculated using a standard shortest path algorithm suitable for a graph with nonnegative edge weights (e.g. Dijktras's algorithm). However, this graph contains more edges than necessary because many potential connections between trains are irrelevant as they will never be used by any passengers (e.g. a train running from node A to B need not be connected to a train running from B to A).

The number of edges in the *period time graph* can be further reduced by a branch and bound approach. The goal is to eliminate all edges that definitely can never occur in any shortest path for any possible timetable. The length of a path in the period time graph depends on the choice of arrival and departure times, because they determine the length of the auxiliary edges. Changing such times can lead to new shortest paths following longer routes, in other words a long waiting time on a shorter route can be

compensated by taking an alternative longer route. Calculating all paths that can possibly lead to the shortest one for a certain timetable creates a list of candidate connections. Only edges that are used by one of these candidates are created in the period time graph.

This is done by calculating all relevant paths between any two nodes in the original smaller graph structure, which will then be mapped into the period time graph. Algorithms for computing the k-shortest path (like Yen's algorithm [14]) can be used for this. The number k is determined by estimating a bound for acceptable deviations. Only edges that can be derived from these relevant paths and the lines that travel on their edges are created in the *period time graph*. In the OptiTakt evolution, Yen's algorithm was later replaced by an implementation of the MPS algorithm that performs better in the Java implementation [11].

Using this approach all alternative connections between node pairs can be determined in advance. Later changes of arrival or departure times do not lead to a new calculation of paths and path length. For finding the shortest connection, the list of candidate connections belonging to each node pair has to be resorted according to the new timetable values. This is implemented in the OptiTakt calculator and used during the optimisation and by the OptiTakt editor front-end in particular.

3.2 Frequency of service, costs and network efficiency

Neither the TLT nor the TWLT ratio reflect cost issues which, for example, have to do with frequency of service. Particularly a locally better period achieved by a higher frequency of connections that exist in the global period P does not have any effect on these indicators, although the schedule with higher train frequency is obviously better – but for the price of higher costs. Consequently we have extended our scores to consider the number of connections between two nodes in the period P.

So far we have multiplied given weights with the loss time for each pair of nodes. Here only the best connection for that pair contributed to the score since we assumed that each passenger arrives just in time for this connection calculated by OptiTakt. This is now extended by our *random arrival* approach. In our original model, waiting time for the departure of the first train was not counted. In the extended model we distribute the weight of passengers travelling between a given pair of nodes evenly over the whole period assuming that passengers arrive randomly at the station. If no weights are given we take one passenger per point of time in the period. The additional waiting time at the departure station is called *starting time*. We then look for each point of time t in the period (from 0 to P-1) for the best connection to the target station. For each point in time in the period we get a loss time by subtracting the ideal travel time from the actual value. This time is called $\delta^t_{v,v'}$. Summing over all node pairs and all time points in the period we get the PLT ratio (for *Period Loss Time*).

$$PLT = \sum_{v,v' \in V} \frac{w_{v,v'}}{P} \sum_{t=0}^{P-1} \delta^t_{v,v'}$$

Period Loss Time

Note that for each t the chosen train does not necessarily have to be the next one as there might be a faster one departing later in time but arriving earlier at the target.

If we assume that only one train leaves per period we get P*(P-1)/2 additional waiting minutes for a given period P. For P=60 this means 3540 and for P=120 7140 minutes respectively (taken over a horizon of 120 minutes).
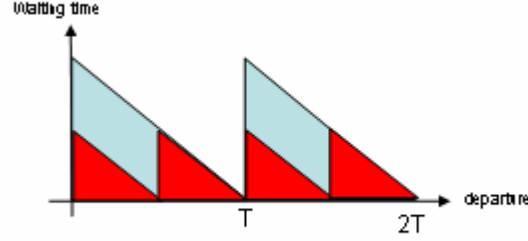

Fig. 2: Distributed arrival

Figure 2 shows the effect of doubling the frequency of trains in the period: the overall waiting time (the area in the triangles) is approximately reduced by a factor of 2. We assume a period of 60 to be the normal case and thus we use the value for P=60 to normalize our measures for each node pair by dividing the sum of for each node pair by 3540. The normalized PLT ratio is called NPLT.

$$PLT = \sum_{v,v' \in V} \frac{w_{v,v'}}{3540 \cdot P} \sum_{t=0}^{P-1} \delta^t_{v,v'}$$

Normalized Period Loss Time

The concept works for additional trains that do not run in a regular periodic scheme as well. It can easily be shown that a regular service is better than an irregular one with the same number of trains. A value close to 1 for a summand of the outer sum indicates a quality equivalent to a period of 60 minutes for the node pair v, v' belonging to that summand. Instead of taking the sum of all these values (as in NPLT) we calculate the mean value (MNPLT = Mean Normalized Period Loss Time) over all pairs as the quality measure to be used in our further calculations.

Of course a higher supply of trains leads to higher costs. Therefore we must further extend our quality measures to relate schedule quality to the expenses required to achieve that quality. The expenses are measured in *total mileage (TM)* given in km. Now we can define the net efficiency (NE) ratio to be:

$$NE = \frac{1}{MNPLT * TM}$$

Net Efficiency

A better time table is characterised by lower MNPLT values, thus the net efficiency NE of a timetable can be improved either by reducing the value of MNPLT (i.e. by higher quality) or by reducing TM (i.e. the costs).

This will be illustrated in the following example. Let Var1 and Var2 be two different alternative solutions for a schedule. The period is P = 120 for every (straight or dashed) line.

In Var1 the departure times for the two parallel lines from C to D are close together, in order to make changeover between the lines (running e.g. from A to F and from B to E) possible. In Var. 2 we add two supplementary lines and adjust the departure times between C and D to form a period of 60 minutes. The MNPLT values are: 2.02 for Var1 and 1.28 for Var2, respectively. This means that Var2 has a higher service quality than Var1. Indeed Var1 is basically a 2-hour period schedule while Var2 offers hourly services.
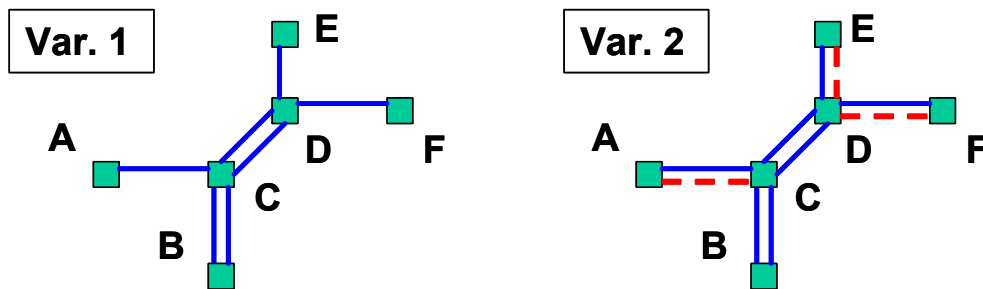

Fig. 3: Two alternative schedules

At this stage cost calculations come into play. For illustration purposes, let all distances between any two adjacent nodes be 0.5 (just counting the number of segment services in both directions). Then we get TM = 7 for Var1 and TM = 10 for Var2. This yields:

Var1: MNPLT=2.02, TM = 7→ NE = 1 / (MNPLT * TM) = 1 / 14.14 = 0.0707

Var2: MNPLT=1.28, TM = 10→NE = 1 / (MNPLT * TM) = 1 / 12.8 = 0.0781

We conclude that Var2 does indeed produce higher costs to achieve the quality improvements. But these expenses pay off, as the quality is improved more than proportionally. This is expressed by a higher net efficiency ratio.

Figure 4 shows reciprocal values for NE. The figure illustrates that a better net efficiency can be achieved either by improving the service quality with relatively few additional costs or by reducing the costs in such a way that the service quality is almost unaffected.
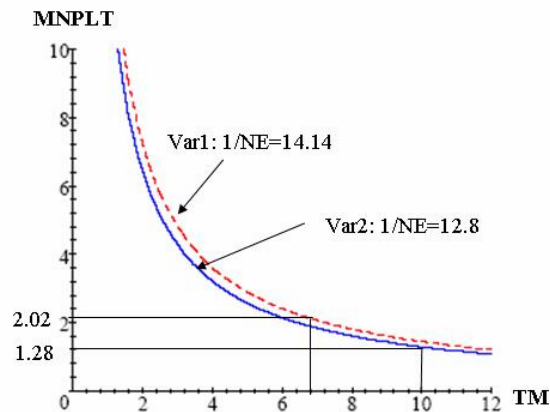
Fig. 4: Graph for net efficiency of Var1 and Var2

3.3   Important OptiTakt features (summary)

The OptiTakt tool was originally implemented as a prototype using AI and object orientted software development techniques (Lisp/CLOS). Since 1998, a Java-based version of the tool is operational and is continuously being improved. The present version offers (among others) the following features:

- Entry of given network and timetable data by a graphical editor, direct manipulation of the network structure and of all timetable data via the graphical interface;

- Calculation of derivable (arrival and departure time) data for full lines;

- Calculation of various scores and indicators of timetable quality, including weighted scores;

- Automated comparison of several variants of timetables for the same base network based on various quality scores;

- Multiple views on timetables such as network view, table (railway guide) view, path-time diagram, geo (true coordinate) view including background map;

- Formatted output and print functions for networks, timetable variants, timetable views, matrices, scores and comparison tables.

3.4   The OptiTakt architecture

The OptiTakt system is built of independent components that communicate over well-defined interfaces. The architecture extends the well-known MVC pattern (cf. fig. 5). Network structures are transferred in an XML like language. Events resulting from user interactions through the graphical user interface are propagated from component to component. The components available at the moment are described in the following sections. New functionality is being implemented in further components.
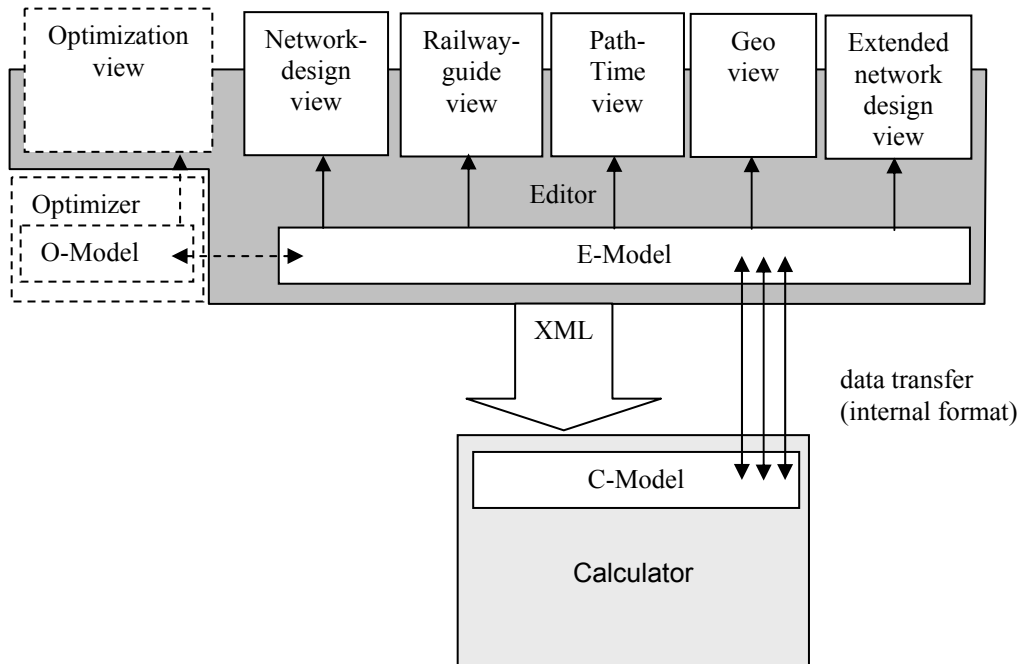
Fig. 5: The OptiTakt architecture

The OptiTakt calculator

The OptiTakt calculator performs all calculations based on the graph structures described above. Here the algorithms for computing alternative paths in the network (see above) are implemented. The model works with paths that represent the routes through the network and connections that map paths to the structure of lines. The object-oriented structure – especially the use of the so-called *observer pattern* - enables the system to perform complete network changes, i.e. changes at one particular point are automatically propagated through the complete network.

The calculator reacts to events raised by other components (e.g. signalling a changed arrival, departure or travel time) by automatically adjusting the network to a consistent state and reflecting the new state to the other components of the system. Thus changes of timetable settings will automatically be propagated through the complete timetable adjusting all dependent values according to the new data.

The OptiTakt calculator is also responsible for calculating all quality indicators (see above) and providing all data needed for schedule analyses.

The OptiTakt editor

The Optitakt editor forms the Graphical User Interface (GUI) for the calculator and future extensions. The editor offers multiple views on a timetable and on the underlying network: A *network design* view, several *table-based* views including a *railway guide* view, a *geo* view, an *extended network design* view, a *path-time* view and an *optimisation* view.
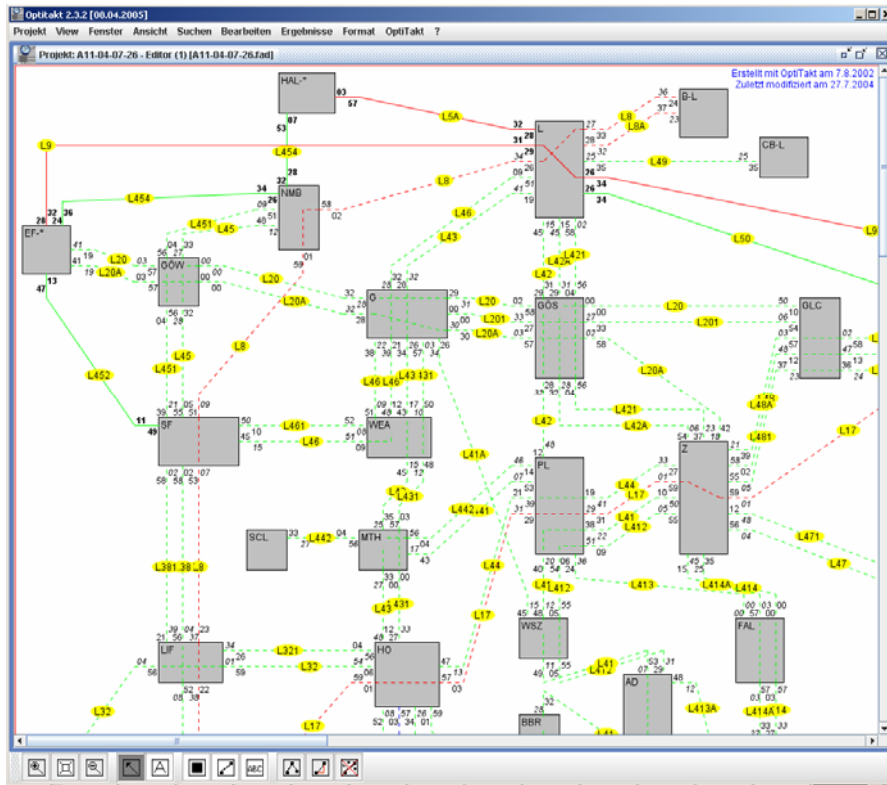

Fig 6: Network design view

At first the editor offers a CAD-like *network design view* (cf. fig. 6). The user can easily add, modify or delete stations and their connections using *drag and drop* functions. In a second step he can combine adjacent connections to railway lines. The periodic departure times of the railway lines calling a station can be entered through little boxes at the margin of the corresponding station node.

A second view shows arrival and departure times for all lines like a railway guide (*railway guide view*). Editor and calculator are connected by so-called *Observer / Observable-Objects*: modifying any departure time of a railway line through an editor view causes the calculator to compute new arrival and departure times for the full line. These values are passed back to the editor and displayed there. In order to compute the

new departure times, the calculator requires the specification of the minimal running times for a connection between two stations. These values and other attributes of the stations and connections can be entered in special dialogs.
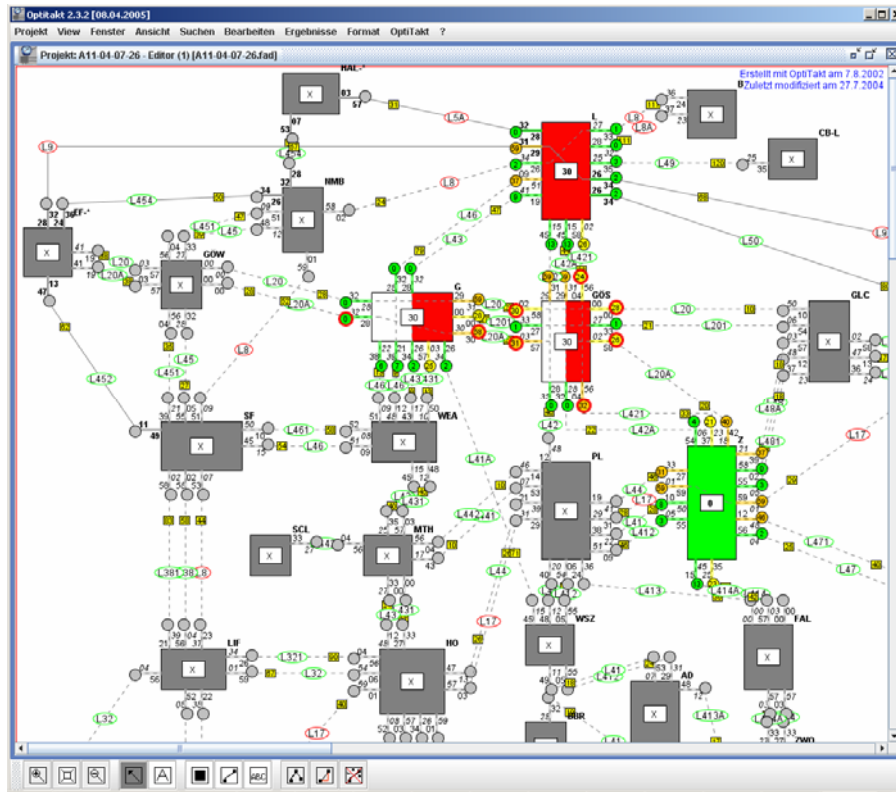

Fig 7: Extended network design view

Furthermore the editor supports the analysis of periodic timetables. In the *extended network design view* (cf. fig. 7) the user can select a primary rendezvous time for each station (e.g. 0 or 30). Periodically, at this minute changing from one train to another should be possible without long waiting time. Resulting loss-times are computed after each user input and are indicated by different colours depending on their impact. This way the user immediately knows which departure times have to be reconsidered.

If the user supplies coordinates for each station and a geo-referenced map of the area, the editor offers an additional *geo(graphical) view* with the stations at their real positions in the map. Provided that it is a thematic map indicating data on population density, the editor is able to calculate weights for each station by analyzing the background colour of its surrounding area. These weights can, for instance, be used by the calculator to compute weighted quality scores for different schedules or by the optimization module to detect important stations and connections.
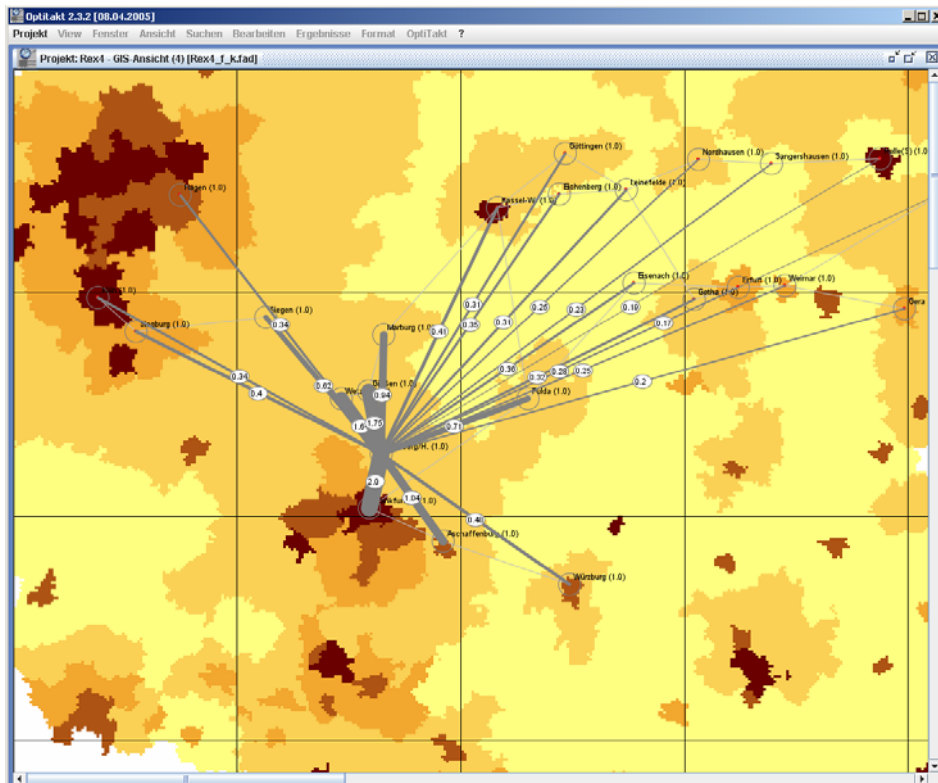
Fig 8: Geographical view

The *path-time view* shows a path-time diagram for all railway lines selected by the user. The flatter a line appears in the view diagram, the faster it is. Vertical interceptions indicate stop times. Meeting and overtaking events of two different lines appear as crossing lines. This is particularly important for single-track lines. The path-time-view also offers *drag and drop* functionality to modify departure times.

Currently a further editor view is being developed. It will allow adaptation of the parameters of the optimisation module and monitor the optimisation process (see also section 5).
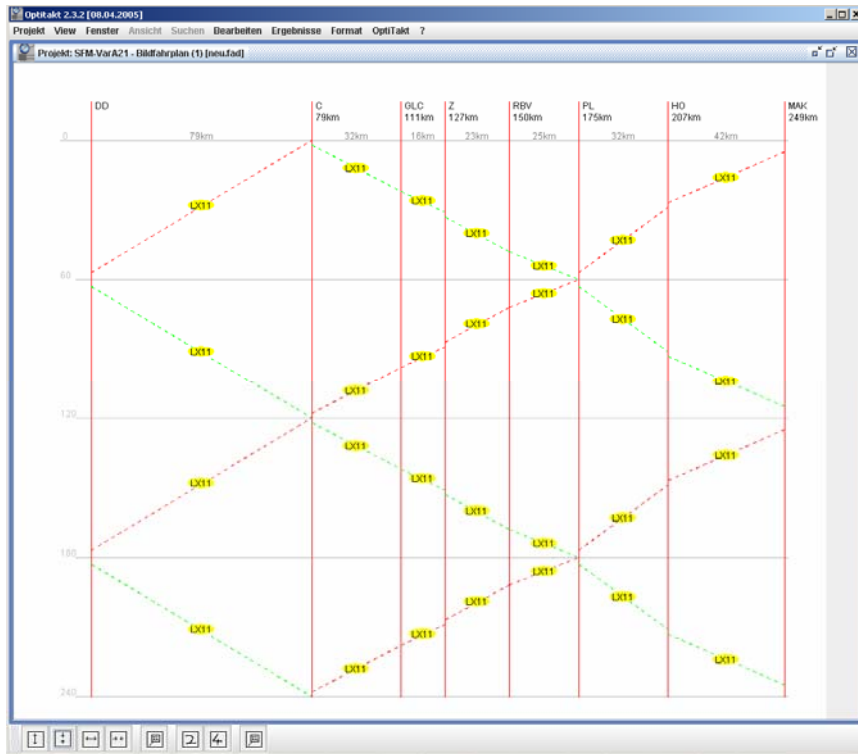
Fig 9: Path-Time view

4 Projects with OptiTakt

Our OptiTakt tool became operational in 1998 and since then it has successfully been applied in various IPT development and assessment projects. In the following, we briefly report on three concluded and one current project:

- **Project Northern Bavaria (NoBy 1-2):**

  The goal of this project was to develop an IPT for the northern part of Bavaria (approx. north of the line Würzburg – Nürnberg – Passau up to the Thuringian/ Saxonian borderline) and surrounding regions (cf. also [3]). A fairly complex network including 39 nodes and 35 railway lines had to be treated. Particular attention had to be paid to integrating the various levels of trains: very fast long-distance, fast medium-distance and rather slow short-distance trains. For this reason the project was carried out in two steps representing two planning levels.

  The first level focussed on long- and medium distance train connections. The principal task here was to fit the 2-hourly running fast RE (medium-distance) lines into the (more or less predefined) frame of fast long-distance trains. This was achieved by determining a small set of (3 or 4) of principal RE nodes which provide optimal change conditions by a sharp +00 or -00 node time (also called *zero hubs* in

the literature). From this timetable skeleton, all other lines and connections could be constructed in an interactive way, where automated timetable generation steps alternated with manual adjustments of the (human) planner. This planning phase resulted in 9 variants, which were compared, evaluated and ranked by our tool to give customers a solid base for their timetable decisions. Eventually, two variants were selected for further investigation in the second phase.

The second level had to extend the network including all short distance lines, trains and connections. On the basis of the two selected variants, 13 further variants were constructed in an interactive way. In total, on the two levels 22 variants were developed and evaluated. Recommendations to the customers were based on the two leading variants. Major parts of the recommendations have been achieved in recent years. Others could not yet be implemented, mainly due to political obstacles (cf. also below, project SFM).

- *Project Four-State Network (VLN):*

  This project focused on IPT integration. In Germany, the so-called Bahnreform (railway reformation process) in the mid-nineties resulted in a regionalisation of the medium- and short-distance connections, i.e. responsibility for these was transferred from the former Federal Railway Company (*"Bundesbahn"*) to state-based regional Railway Management organisations as e.g. the Bayerische Eisenbahn-Gesellschaft (Bavarian Railway Corp., BEG) in München. Some of the states introduced IPTs in their states or in parts – as did the BEG for Bavaria by their *"Bayern-Takt"* project. However, at the state borderlines the state-specific IPTs often do not correspond to each other and make crossing these borders a tedious and time-consuming task.

  For this reason, four railway management institutions based in three states of Germany and in the North-western part of the Czech Republic started a project to harmonize their regional IPTs and develop a joint inter-state IPT for these four states using our OptiTakt approach. Faced with a network even bigger than in the NoBy project we adopted again a two-level approach. The final network comprised 50 nodes, 35 lines and a total of 22 variants was constructed and evaluated. Special problems resulted from the fact that parts of the regional lines in Southern Saxony have not yet adopted periodic and symmetric timetables. Moreover, in the Czech Republic, reformation of timetables is still in its beginning and up to now IPT principles are being adopted only on the express train level.

- *Project Nordfranken (NoFra):*

  This project had a particular focus: Our customer organisation planned to upgrade the frequency of service for medium distance (RE level) trains in northern Bavaria from 2-hourly to 1-hourly service and wanted a quantified evaluation of the expected effects on customer acceptance. In order to quantify these effects, special frequency-sensitive quality scores were developed and employed in the project (cf. section 3.2). The OptiTakt study resulted in a 16-20 % higher customer acceptance score and a strong recommendation of the upgrade. By the end of 2004, main parts of the upgrade had been implemented and the service quality in this region was considerably improved. Further improvements will follow in the coming timetable period.

- *Project Sachsen-Franken-Magistrale (SFM):*

In this case our customers form a City Network of five municipalities in Northern Bavaria and southern Saxony which are linked by a double-track main line called *Sachsen-Franken-Magistrale*, short: *SFM*. Recently, this line was modernised and equipped for tilting technique. It is operated by regional trains and – until last year – it was connected by a 2-hourly fast long-distance train (IC Nürnberg – Dresden). For various political and technical reasons, this long-distance service was virtually ceased last year. At the moment, only a few IC trains per day are left which operate slower than the regional trains for a considerably higher price. The IC service is not integrated with the regional and local lines and the present timetable of a low quality comparable to German post re-unification levels times 10 years ago.

On the other hand, the topographical and infrastructural conditions for installing and running an IPT with the SFM as its backbone line are pretty good: They allow IPT-compatible travelling times between the principal nodes Nürnberg, Bayreuth, Hof, Plauen, Zwickau and Chemnitz. The benefits of the IPT approach are being illustrated and seven timetable variants are being constructed to support our customers in their demands to improve the present unsatisfactory situation and install an IPT in this important inter-state region of Germany.

5 Current and future research

Since its first version in 1998, the OptiTakt tool has been continuously improved, re-implemented and extended. The original system used simple optimisation heuristics to construct and evaluate timetables that performed sufficiently well with small and medium-sized networks. Today we are able to treat medium-size networks with about 50-60 nodes and perform rather sophisticated calculations in acceptable response time.

Current research focuses on two extensions: First, we are investigating the application of improved and more efficient heuristics together with a multi-level approach in order to handle larger networks. *"Multi-level approach"* means: we are trying to further automate the process described above of constructing complex time-tables in several steps proceeding from a high level of fast, long-distance trains down to detailed timetables including all regional and local trains. Another approach focuses on integration of existing regional IPTs to larger inter-regional solutions as inspired by the VLN project.

Second, we are aiming for a higher automated timetable construction process which is, for example, essential for performing more sophisticated simulation tasks and for freeing the timetable planner from tedious, less creative parts of his interactive work. Such a process must use techniques going beyond the well-known *branch and bound* algorithms, which cannot satisfactorily deal with local (but not necessarily global) optima. A possible solution may result from our current research on combining non-deterministic approaches such as agent technology and genetic algorithms.

We are convinced that both research issues have an immense application potential. The more regional and state-limited networks are merging and their operators are trying to use synergetic effects resulting from their integration, the more multi-level time-tabling will be required and used in order to construct large IPTs on the nation-wide and European level.

Furthermore, the rapidly growing costs of large infrastructure projects (like high speed lines or total reconstruction of city main stations) and financial constraints resulting from cuts of public budgets will increase the demand for more intelligent, efficient and (relatively) low-cost solutions. Automatic optimisation of networks and simulation of the effects of potential infrastructure investments are tasks which can well be done (and should be done!) *before* starting huge infrastructure building projects (instead of doing such analyses *afterwards*). This way, following the IPT principles und using the appropriate tools can lead to much more efficient networks and timetables for lower costs in the future.

6 Conclusions

In the European railway systems, major changes have occurred in the last twenty years. State-owned, centralised railway companies have been (partly) privatised, re-organised and de-centralised. Single railway lines and regional networks have been improved and have attracted a larger number of passengers by better service and increased efficiency. The network efficiency depends largely on the quality of timetables for which the IPT concept is essential. Positive experiences with IPTs have been made in several central-European states and regions such as the Netherlands, Austria and most of the German states ("Länder"). An outstanding example of successful use of an IPT for a whole country is Switzerland. There the IPT concept forms the backbone of the so-called "Bahn 2000" system, which was favoured by a plebiscite in the 1980's and since then has been implemented step by step. The major underlying concept is that infrastructure planning has to *follow* the timetable requirements and *not* vice versa. This development culminated in the recent inauguration of a high-speed segment on the line Zürich-/Basel-Bern which enabled high-quality train connections not only to users of that particular line but virtually to every Swiss citizen [4].

In Germany, after a promising starting phase of installing the IC system in the 1980s and regional IPTs in the 1990s, other goals and strategies have dominated the infrastructure politics and thus have constrained the chances for implementing good IPTs. The construction of high-speed railway lines has been given priority over other demands and IPT requirements are often neglected. As a result, huge financial efforts are not justified by a corresponding gain in overall network quality and, consequently, do neither lead to a better overall net efficiency nor to the expected increases in passenger numbers (cf. e.g. [6, 7]).

On the other hand, recent studies have shown the great potential of the IPT concept and an IPT-oriented infrastructure politics for the development of high quality, customer-friendly railway networks [12, 13, 5]. We are convinced that the future of European Railway systems is highly dependant on their ability to offer regular, high-quality services on densely connected and frequently operated networks which are best supported by following the IPT principles. A tool like OptiTakt offers the railway planner the adequate support to calculate, compare and evaluate existing and future timetables. For decision makers it is the appropriate tool to forecast the effects of potential infrastructure projects and help to invest the scarce financial budgets in an optimal way.

References:

[1] H. Domschke: *Schedule synchronization for Public Transit Networks* (1989), OR-Spektrum (1989) 1:17-24, Springer-Verlag 1989

[2] M. Guckert: *Anschlußoptimierung in öffentlichen Verkehrsnetzen – Graphentheoretische Grundlagen, objektorientierte Modellierung und Implementierung*. Dissertation, Univ. Marburg 1997

[3] M. Guckert, W. Hesse, J. Schneider, A. Schulz: *Werkzeuggestützte Entwicklung eines Integralen Taktfahrplans für Nordost-Bayern*. In: Internationales Verkehrswesen 6/2000, S. 264-268

[4] Eisenbahn Revue International. Sonderheft zur Eröffnung von Bahn 2000. Minirex Verlag, Dez. 2004

[5] W. Hesse: *Konzept für ein System von Bahn-Netzknoten in Süddeutschland*. Eisenbahn-Revue International, Heft 5/2000, S. 236-239, Minirex-Verlag, Luzern 2000

[6] W. Hesse: *Hochgeschwindigkeit und ihre Folgen - das Beispiel München-Nürnberg*. Proc. Kongress "Mehr Züge für das Land" - Bürgerbahn statt Börsenbahn. Kassel, März 2002

[7] W. Hesse: Verpasste Knoten - verpatzte Knoten - ein kritischer Blick auf die Netz- und Fahrplangestaltung der DB. In: Viele Bahnen - ein System. Tagungsband Horber Schienentage 2003, ProBahn Verlag 2003 und in: Der Fahrgast – ProBahn Zeitung 3/04, S. 20-25 (2004)

[8] M. Kolonko, O. Engelhardt-Funke: *Genetisch optimierte Fahrpläne und Kosten-Nutzen-Analysen für Verkehrsnetze*. http://www.math.tu-clausthal.de/ Arbeitsgruppen/Stochastische-Optimierung/HiTT_Deutsch/

[9] C. Liebchen, M. Proksch, F. H. Wagner: *Performance of Algorithms for Periodic Timetable Optimization*. 9th International Conference on Computer-Aided Scheduling of Public Transport, San Diego 2004

[10] C. Liebchen: *Symmetry for Periodic Railway Timetables*. Electr. Notes on Theor. Comput. Sci. 92: 34-51 (2004)

[11] E. Martins, M. Pascoal, J. Dos Santos: *A new algorithm for ranking loopless paths*, (1997), Departamento de Matematica Unversidade de Coimbra, Portugal

[12] ProBahn: *Der letzte Fahrplanwechsel – Konzept für einen bundesweiten Integralen Taktfahrplan mit schnellem Fernverkehr*. ProBahn e.V. 2000. http://www.pro-bahn.de/pbz/itf_broschuere.pdf

[13] VCD: Bahn 21 – *Eine Strategie für die Bahn von morgen*. Gutachten für den VerkehrsClub Deutschland (VCD) e.V. (2004) http://www.vcd.org/themen/download/vcdstudie_bahn21.pdf

[14] J. Yen: *Finding the k-shortest loopless path in a network*. Management Sciences (1971), pp.712-716