AUTOMATED GENERATION AND OPTIMIZATION OF PUBLIC RAILWAY AND RAIL FREIGHT TRANSPORT TIME TABLES

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Abstract: *Railway traffic now and in future faces ever-growing challenges. On the one hand, infrastructure measures must be planned and in the medium respectively long term corresponding operating programs have to be generated. On the other hand, in the short term economical and political reasons exert increasing influence on the requirements of timetabling as well. Hence, they can hardly be efficiently handled with manual effort. Consequently, it exists the need for highly optimized, automated algorithms and its corresponding intelligent conjunction. A state-of-the-art realization is reflected in the software system TAKT, which is developed in close cooperation with the German railway company DB Netz AG. The implementation offers a complete new approach to solve the problems like computing conflict-free, optimized time tables or searching, optimizing and maximizing rail freight transport train paths based on an existing operating program. In this work, the different program component and their interactions among each other will be presented and discussed.*

Keywords: PUBLIC RAILWAY TRANSPORT, RAIL FREIGHT TRANSPORT, TIMETABLING, PERIODIC EVENT SCHEDULING PROBLEM, OPTIMIZATION

1 Introduction

In especially complex networks timetabling is a protracted process, which, despite computer aided methods, comes along with a high manual effort. The reason is based on the huge amount of technical, operative and economical requirements and its dependencies among each other. Hence, the underlying infrastructure, the train characteristics and its resulting driving dynamic properties as well as the conflict-free positions of the individual train paths exert decisive influence on the time table. Additionally, the operational requirements, for example connections, symmetry and locomotive crew changes, play a major role. Not negligible are economical factors, such as the demand of specific train paths and their qualities (running times, waiting times, transfer times). Consequently, timetabling must be regarded as the core decision for an economically reasonable business.

Due to the large amount of constraints and the operator's obligatory needed knowledge about geographic circumstances as well as the infrastructure, the manual editing is only possible for small subnetworks.

Particularly in the strategic long-term planning timetabling poses an outstanding challenge. The consideration of different planning intervals inevitably induces different infrastructure states, which is the basis in the generation of different time table variants. Verification and necessity respectively potential usages of planned con- and reconstruction measures can only be served by analysis and comparison of different time tables. Furthermore, the manual methods for the generation of diverse time table variants, in case of a predetermined time quota and budget, rapidly reaching its limits.

This is the starting point for the software system TAKT.

In recent years, the group of the chair of traffic flow science at TU Dresden in close collaboration with the DB Netz AG have successfully developed a software system, which supports the decision maker in his tasks for the strategic planning. The software system TAKT automatically calculates and optimizes periodic train paths for complex railway networks by an innovative approach in strategic passenger's and freight train's timetabling. This results in different variants of strictly synchronized and conflict-free timetables. Therefore, the train path and time table compositions can be considerably be improved and it extends more variety to the solution of the strategic tasks.

2 TAKT

Figure 1 displays the scheme of the software system TAKT that consists of several modules, which interact in different ways. Based on the infrastructure and train data, model trains are constructed by means of the model train generator. This defines the operating program. Subsequently, the constraint system can be generated and is represented as periodic event scheduling problem (PESP) and solved by an appropriate solver. If feasible, the PESP solver provides a strictly synchronized, feasible time table, which may be optimized afterwards.

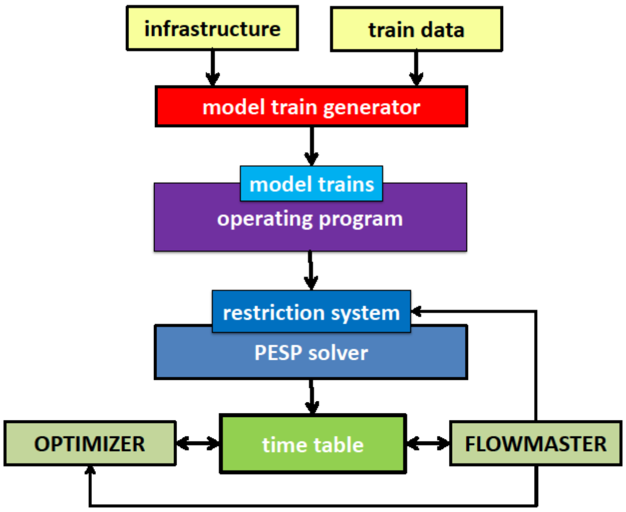

Fig. 1 *Timetabling with the software system TAKT, its different modules and their respective interactions*

2.1 Input

Infrastructure and train data represent the database of the software system TAKT. As raw data for the description of the infrastructure serves the XML-ISS files, which contain the detailed resolved track diagram data. Especially all rail track elements, such as switches, crossings, bumpers and signal positions, as well as stations and train runtime points. Likewise, the track data, such as speed limitations, grades, equipped with overhead contact wires and continuous train control (LZB) equipment, are included.

Figure 2 displays an example for the most detailed infrastructure in the software system TAKT.

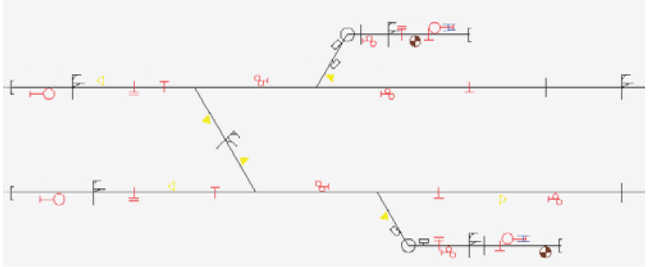

Fig. 2 *Illustration of the track-accurate infrastructure of a two tracked station [Screenshot TAKT]*

Furthermore, the infrastructure data contain all information about traction units (locomotives and railcars) like mass, length, maximum velocity as well as train and tractive power resistance coefficients. Thus, the train powers and resistance forces can be inferred, which are essential for the driving dynamics calculations.

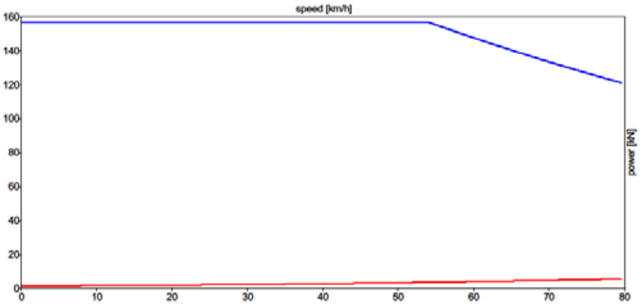

Fig. 3 *Train power (blue) and train resistance (red) of a traction unit against velocity [Screenshot TAKT]*

The model trains can be directly designed in the software system. For that purpose, the model train properties are defined by corresponding input masks. Those properties are train class, traction unit(s), amount of wagons, total weight, total length, period, stations, minimum stop times, main or non-busy period. In Addition, the connections, periods and the allowed symmetry deviations have to be entered.

With regard to complex projects with a high amount of model trains, the manual creation of model trains is not suitable. In order to counter the severe manual effort a standardized XML-KSS interface is implemented, which allows importing complete operating programs with all needed information.

For every operating program's model train an optimal route is calculated by a novel routing algorithm [5]. These routes are characterized by the shortest running time between two stations as well as the usage of the main track. Subsequently, based on the found routes the driving dynamics of the model train are calculated.

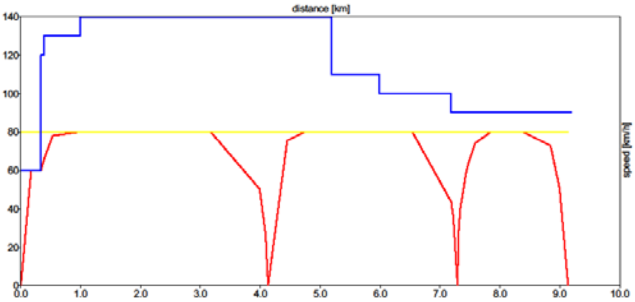

Fig. 4 *Velocity profile of a model train, displayed are the maximum train velocity (yellow), the maximum track velocity (blue) and the current train velocity (red) against the distance [Screenshot TAKT]*

The driving dynamics' computation is the requirement for the determination of the blocking time (see Figure 5) and thus, for the computation of the minimal headway. The driving dynamics calculation algorithm is based on a path step procedure using all relevant information, for example track grades and the allowed maximum track speed, taking the traction unit class and their respective equipment into consideration. Additionally, the calculation of the blocking time distinguishes between traction units with intermittent automatic train control (ATC) and continuous train control (LZB).

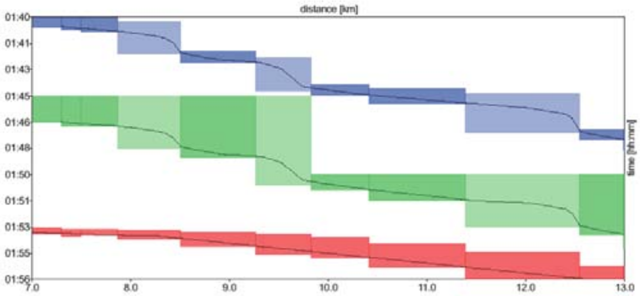

Fig. 5 *Diagram of the blocking time for three different model trains: local passenger train with LZB (blue), local passenger train without LZB (green) and non-stopping ICE with LZB (red) [Screenshot TAKT]*

Finally, we can generate the restriction system by the collected information, such as running times, minimal headway, periods, connections and symmetry settings. This system represents all the properties of the operating program in form of a PESP model and can be solved by means of a PESP solver in order to generate possible time table variants.

2.2 Periodic event scheduling problem

The periodic event scheduling problem (PESP) has been introduced by Serafini and Ukovich in 1989 [6], which is subject to a periodic event network. This periodic event network (PEN) is a graph that consists of a given period, a set of nodes (events) and a set of edges (constraints), each of which connects two different events. Each event happens recurrently in time modulo the given period, which is called potential of the event. In the area of timetabling, these events may represent the arrival and departure event of a train in a station. The edges respectively constraints define the sequence in time for each event. This is given by the lower and upper bound for each constraint, for example the minimal and maximal running times of trains between two stops. A constraint is said to be valid if and only if the difference of the potentials of the two following corresponding events modulo the period are in between the lower and upper bound. A schedule, which is an assignment of a potential for each event, is feasible if and only if all constraints are valid.

The PESP is the decision problem whether it exists a feasible schedule for a given periodic event network or not. In case it does not exist any feasible schedule for a specific PEN, the instance is called infeasible.

For example, Figure 6 displays the model of a trip between a departure event in I and an arrival event in J. The needed running time from I to J is set to 20 min. The modeling of the waiting time in station J is given by a constraint as well. Here, the minimal waiting time and maximal waiting time is 3 and 5, respectively.

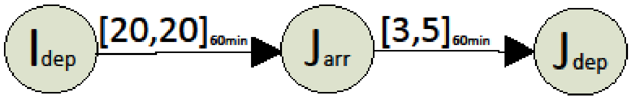

***Fig. 6** Illustration of the modeling of a trip between a departure event I to an arrival event J, with a given running time with 20 minutes and a defined waiting time of 3 up to 5 minutes in J*

The software system TAKT generates the PESP graphs respectively PENs with respect to running times, minimal headway, waiting times, connections and symmetry settings. The possibility to show the graph visually is given as well.

Once the PESP solver, which is based on a novel approach [1, 2], calculated a feasible schedule for the restriction system, the results are evaluated and interpreted by the software system TAKT and the trains' departure events adjusted accordingly. If the PESP solver has proven that it does not exist any feasible solution, then the PEN can be resolved by extracting so called local conflicts and resolving each of which.

A PEN is a local conflict if and only if it is infeasible and by removing any constraint it becomes feasible. These small conflicts can now be handled by linear program (LP) solvers [3, 4]. This is done by minimally relaxing all, except the headway and running time constraints, with respect to a given weight. This optimization is realized in TAKT. If the relaxations shift the restriction system to a feasible one, the gained information (relaxations) will be included into the operating program.

2.3 Rail freight transport

The automatic freight train path generation in the software system TAKT uses a novel algorithm. Based on an existing passenger traffic time table, which has been generated by TAKT in beforehand, the freight train paths are generated and subsequently be maximized. In the latter step, the timetable may not be fixed and thus, increases the capacity possibilities significantly. For the purpose of finding possible paths, a routing algorithm calculates possible reasonable paths, based on a timetable. This means, by means of the blocking time by the passenger traffic, freight train paths are searched on the continuous main track. Imposing conflicts will be evaded by velocity harmonization and the insertion of additional stops. Each new path will consider the already found paths by automatically inserting stops in regular distances on the passing loop. Afterwards, the paths are cut at suitable points, resulting in a set of path snippets.

The set of snippets form the basis for the maximization of the freight train paths by the FLOWMASTER.

The FLOWMASTER offers the possibility to calculate complete, conflict-free paths, based on the set of snippets and the given sinks and destinations. Therefore, the algorithm concerns the restriction system of the passenger traffic and expands it by adding the constraints for the freight transport paths. Subsequently, the resulting new PEN will be solved by the PESP solver.

If this process leads to a valid solution, then calculated timetable will be saved and another path will be included in the next iteration. By increasing the amount of paths the quality of the freight transport paths decreases with respect to waiting times and thus, the total running time. Hence, the possibility exists to analyze and evaluate the different timetable variants among each other

2.4 Optimization

The solutions, which are obtained by the PESP solver, can be optimized in a subsequent process. The optimization idea consists of minimizing the waiting and connection times, based on a reallocation. The optimization's objective is the sum of the weighted waiting and connection times of a timetable. This value should be minimized [2, 3, 4]. Especially for timetables that needed a lot of waiting time relaxations, the optimization can improve the objective a lot and thus, increasing the quality of the timetable.

In the automatic freight train path generation by the FLOWMASTER the sections of this path are connected, for example by stop on stop which comes along with a waiting time. The optimization may result in a state, that the waiting time gets minimized, such that the economical stop is senseless. Consequently, the a posteriori removal of the stop and fitting of the velocity enormously increases the quality of the train.

3 Results and discussion

By the long lasting and close collaboration with the DB Netz AG, the software system TAKT is already successfully applied in practice. A current project engages with the generation of timetable variants of 202x with a planned infrastructure state in this time frame. The focus concentrates on long-distance traffic, regional traffic and rail freight transport for Germany's east. The long-distance traffic is only relevant in the remaining parts of Germany, for this particular project. For this reason, the infrastructure is reduced as much as possible and is fit to the project specifications. The result is based on the most detailed infrastructure for the region in Germany`s east.

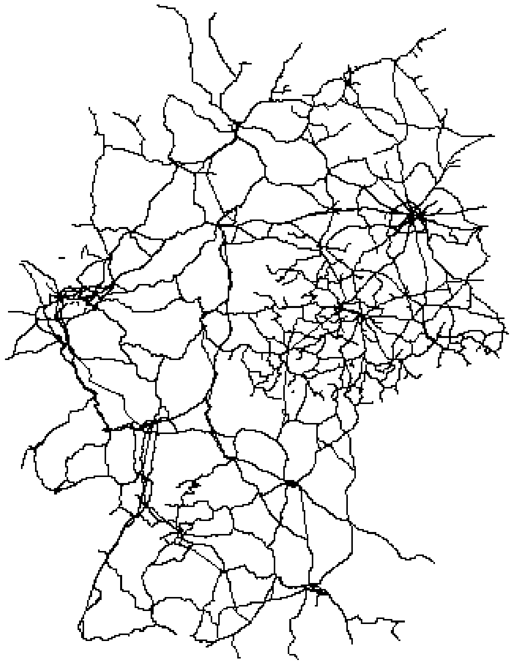

***Fig. 7** Germany-wide infrastructure graph with highest accuracy in Germany's east [Screenshot TAKT]*

In this real-world example the software system TAKT handles a complexity of around 54000 km of track, 182 long-distance train lines and 436 regional train lines. In addition, the restrictions like connections and symmetry are taken into account during timetabling.

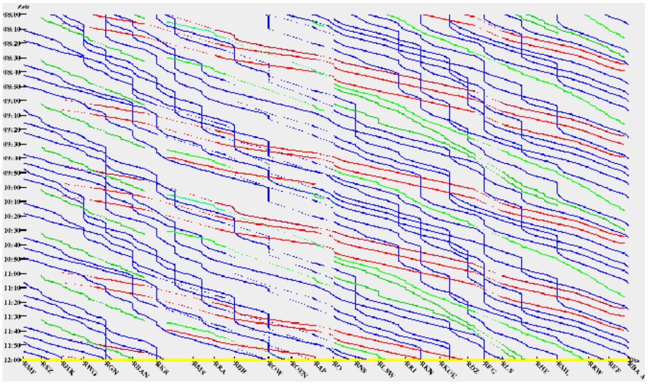

Fig. 8 *Visualization of the train graph [Screenshot TAKT]*

An already finished project handled the maximization of freight train paths on a highly frequented corridor. The focus concentrated on the efficiency and performance of the software system. The operating program was fixed for the given passenger transportation The goal was the generation of freight train paths on this corridor. A subsequent comparison of the number of automatically found paths and their quality with the manual found, gained by an operator, showed doubtlessly the performance of TAKT. With the aid of the innovative FLOWMASTER algorithm, TAKT even increased the number of freight transport trains into the timetable than an operator by hand. However, the quality lowers, when increasing the number of paths, which comes along with longer waiting times and thus, longer running times.

Yet another advantage turned out to be the enormous algorithms' performance. The import of the infrastructure and train data, the timetable's calculation and finally, the generation of freight train paths and its optimization could be solved in a fraction of the time than the manual handling needed. Additionally, a lot of timetable variants could be generated in this time frame, which subsequently could been compared and analyzed.

Since the applications in different projects are practical, you can clearly see by viewing at the results, that the connection and interaction between the different algorithms are very high-performance in the software system TAKT. Even in large projects, which can hardly be handled with manual effort, TAKT proves its cost efficiency.

4 Conclusion

The different technical, operative and economical requirements disprove the manual timetabling especially in large networks, such as Germany, with respect to time consuming processes and cost efficiency. In order to counter this issue, the software system TAKT has been developed by a close collaboration between TU Dresden and the German railway company DB Netz AG. The module based software system calculates strictly synchronized, conflict-free timetables based on infrastructure and train data. Besides the universal interfaces for data exchanges with other programs, TAKT uses a bunch of algorithms, which are solely developed and implemented for the special tasks. The encoding of all timetable requirements into a PESP instance as well as the follow up solving, local conflict resolving and optimization are regarded as the core algorithms.

The system's modular architecture allows an easy combination and composition of the individual algorithms to define solutions for new tasks. Thus, the new system component FLOWMASTER could be developed, which finds potential freight train paths based on a given timetable, maximizes the amount based on the not fixed restriction system and optimizes the generated timetable.

This work presents a software system, which is, to the best of our knowledge, worldwide unique with respect to functionality and function volume as well as performance.

Additionally, the practical application contributes to the influences in the development process regarding habits, proposals and wishes. Thus, the acceptance among the operators could be increased, who sees TAKT as supporting tool and not as competition.

Nevertheless, the further development and improvement of the software system is continuously pushed, not solely regarding algorithms, yet concerning usability and applicability as well.

5 References

[1] Großmann, P.: *Polynomial Reduction from PESP to SAT*, Tech. Rep. 4, Knowledge Representation and Reasoning Group, TU Dresden, 2011.

[2] Nachtigall, K.: *Periodic Network Optimization And Fixed Interval Timetables*. habilitation thesis, Universität Hildesheim, 1998.

[3] Opitz, J.: *Automatische Erzeugung und Optimierung von Taktfahrplänen in Schienenverkehrsnetzen*. Gabler, 1. Auflage, 2009.

[4] Opitz, J.; Nachtigall, K.*: A Modulo Network Simplex Method for Solving Periodic Timetable Optimisation Problems*. Proceedings, OR Saarbrücken, 2007.

[5] Pöhle, D.; Weiß, R.; Opitz, J.; Großmann, P.; Nachtigall, K.: *Innovative automatische Laufwegsuche mittels neuartigem Routing-Algorithmus zum Nutzen der Fahrplanoptimierung*, VWT Dresden, 2012

[6] Serafini, P.; Ukovich, W.: *A Mathematical Model for Periodic Scheduling Problems*. SIAM J. Discrete Math., 2(4):550 –581, 1989.