Applied Railway Optimization in Production Planning at DSB S-tog - Tasks, Tools and Challenges

Jens Clausen

DSB S-tog, Produktionsplanlægningen, Kalvebod Brygge 32, 5, DK - 1560 København V, Denmark, and
Informatics and Mathematical Modelling, Technical University of Denmark, DK 2800 Kgs. Lyngby, Denmark
JenClausen@s-tog.dsb.dk and jc@imm.dtu.dk

Abstract. Efficient public transportation is becoming increasingly vital for modern capitals. DSB S-tog a/s is the major supplier of rail traffic on the infrastructure of the city-rail network in Copenhagen. S-tog has experienced a demand for increasing volume and quality of the transportation offered to the customers, and has concurrently been met with demands for higher efficiency in the daily operation.
The plans of timetable, rolling stock and crew must hence allow for a high level of customer service, be efficient, and be robust against disturbances of operations. It is a highly non-trivial task to meet these conflicting goals. S-tog has therefore on the strategic level decided to use software with optimization capabilities in the planning processes.
We describe the current status for each activity using optimization or simulation as a tool: Timetable evaluation, rolling stock planning, and crew scheduling. In addition we describe on-going efforts in using mathematical models in activities such as timetable design and work-force planning. We also identify some organizatorial key factors, which have paved the way for extended use of optimization methods in railway production planning.

1 Introduction

1.1 S-tog - the Company, Network, and Resources

DSB S-tog a/s (S-tog) is the major supplier of rail traffic on the infrastructure of the city-rail network in Copenhagen. More than 300.000 passengers use the network daily, and the annual turn-over for the company is over 1.4 billion DKK. S-tog has the responsibility of buying and maintaining trains, ensuring the availability of qualified crew, and setting up plans for departures and arrivals, rolling stock, crew etc. The infrastructural responsibility and the responsibility of safety for the S-tog network lie with Banedanmark, which is a company owning the major part of the rail infrastructures in Denmark.

The S-tog network consists of 170 km double tracks and 80 stations. The network consists of two main segments. The circular rail runs from Hellerup in

ATMOS 2007 (p.15-29)
7th Workshop on Algorithmic Approaches for Transportation Modeling, Optimization, and Systems
http://drops.dagstuhl.de/opus/volltexte/2007/1181

the north to Ny Ellebjerg in the south. The remaining network consists of seven segments: Six fingers and a central segment combining the fingers. The network, shown in Figure 1, is serviced by a number of lines. These all pass the central segment, which includes Copenhagen Central (København H).

Most lines in the network are run according to a cyclic timetable and have a frequency of 10 minutes. On the outer parts of one finger this frequency is reduced to 20 minutes, but the assignment of fingers to lines ensures that almost all stations are serviced by 6 trains per hour. There are at daily level appr. 1200 departures from end stations, and additionally approximately 28.000 departures from intermediate stations.

S-tog currently has 104 so-called "1/1-units" each seating 336 passengers, and 31 "1/2-units" seating 150. The units can be combined to various train sizes allowing for more flexible composition of trains. The company employs approximately 550 drivers. At the most busy time of day the network presently requires 86 1/1-units and 27 1/2-units to cover all lines and departures, including standby units (2 1/1-units and 1 1/2-unit).

The passengers of S-tog travel on different types of tickets and cards valid for all public transportation according to a zone system in the Greater Copenhagen area. Tickets are currently not inspected when passengers board or leave trains. Instead, spot inspections are performed by ticket inspectors.

The quality of the service provided by S-tog is measured by two performance indicators: Punctuality and reliability. Punctuality focuses on the number of trains arriving "on time" (interpreted "not later than 2.5 minutes after planned arrival time"), whereas reliability measures the percentage of trains actually run (i.e. not canceled) according to the schedule. The average punctuality must be at least 95 % and the average reliability 97.5 % according to the contract between S-tog and the Ministry of Transportation. This contact also sets lower bounds on the number of trains kilometers run over a time period, and establishes service levels in terms of seat availability compared with the expected number of passengers on departures.

1.2 PPA - The Production Planning Department

The Production Planning Department at S-tog, PPA, is responsible for both the long term planning and the short term planning for both rolling stock and crew, and responsible for the dispatching of rolling stock. The crew dispatching is located in a separate division of the company.

Long term planning includes activities as strategic timetable evaluation, planning of rolling stock circulations and shunting operations at depots, and crew scheduling (both rostering and crew assignment). Short term planning addresses timetable changes due to e.g. track-work and changes in the rolling stock circulations. Also, changes in driver duties due to rolling stock and driver shortages, planning for cleaning personnel, and planning for ticket inspectors is handled by the department.

The plans of timetable, rolling stock and crew must due to the contractual obligations allow for a high level of customer service, be efficient regarding use

Fig. 1. The 2007 S-tog network.

of resources, and be robust against disturbances of operations. It is a highly non-trivial task to meet these conflicting goals. In the recent years S-tog has therefore on the strategic level decided to use software with optimization capabilities in the planning processes. Such software is in general acquired from software vendors. S-tog has as a consequence established an Analysis Section responsible for data analysis and system knowledge, but also with capability of developing in-house tailored solutions to planning and dispatching problems based on advanced optimization and simulation techniques. Even though the introduction of new methods and software in the planning process has lead to an increase in cost for salary and IT-systems, the overall cost reductions in the company is more than twice the budget of the entire production planning department. These reductions are obtained both on the operational level and on the strategic level, and both rolling stock and crew planning contribute to the result.

Due to the sequential characteristics of the resource planning process in S-tog, the time span from establishing initial conditions for the production to calculation of an estimate of the actual costs is large. The planning is initially done for each day type (Weekday, Saturday or Sunday), and is starting from a public timetable. From this a rolling stock plan is made, and the plan for the crew can then be prepared. Thereafter, it is possible to calculate the cost for operating the public timetable. Each planning step is time consuming, and it is a strategic aim to be able to evaluate a plan as quickly and precisely as possible.

The staff at PPA currently consists of 10 crew planners, 5 rolling stock planner, 9 rolling stock dispatchers, 7 academic developers/analysts, and 4 managers. In addition 3 persons are employed in connection with IT-system development (vendor contact, testing, etc.). To ensure up-to-date knowledge and development, S-tog also partly funds 2 Ph.d.-students. The planners typically have more than 20 years of experience with the daily operation of S-tog.

1.3 Contribution

Through a thorough review of problem areas and the mathematically based solution methods used in these by a modern passenger transportation company as S-tog, the current paper aims at enhancing the understanding and knowledge of the optimization methods having proved their value in practice.As the operational context and organizatorial environment plays a key role in creating a positive attitude towards such activities and developments, the paper describes the operational and problem context rather detailed. The goal is that the paper may serve as inspiration both for researchers working with optimization problems with potential applications in railway optimization, and for railway operators, who have not yet taken the step of including planning tools based on mathematics and IT in their operational context.

1.4 Outline of Paper

First we briefly comment on the strategic activities in PPA regarding timetabling. We then focus one by one on the different resources of the entire daily operation of S-tog. For each resource we first describe the operational conditions and the details of the daily operation. Then we describe the planning and dispatching tasks handled by PPA, the software used (also briefly mentioning the underlying methods and techniques), and finally the challenges we expect to meet both in the immediate future and in a longer time perspective.

Since the success of using advanced software tools is intimately related to organizatorial issues, we also briefly comment on the key factors necessary for such a success.

The conclusion sums up our experiences and discusses the pros and cons for a company as S-tog in connection with the use of advanced tools based on mathematics and IT.

2 Strategic Timetabling

2.1 Designing timetables

As mentioned S-tog operates the trains according to a periodic time table. The task of designing this timetable is currently the responsibility of another department in the organization, where each proposed timetable is evaluated against contractual obligations and safety regulations.

Traditionally the trains in the timetable has been of two types: Fast trains and stop trains. Passengers living close to outer terminal stations of course prefer the fast trains since these provide a shorter traveling time. Passengers from minor stations on the network on the other hand prefer that all trains stop at these.

Accommodating both types of trains in a timetable can only be achieved at the expense of service: Even though all stations are serviced with two trains every 20 minutes, some stations may be served regularly every 10 minutes whereas other may have up to 18 minutes between the two trains.

Since PPA is responsible for planning the resources necessary for operating a timetable, it is of prime importance to be able to evaluate existing timetables and new proposal from an operational perspective. In order to be pro-active in this context, PPA has therefore developed an in-house tailored model for time tabling. This model is based on an integer programming formulation of the periodic time tabling problem, which is able to take into account standard constraints as headway between trains, preferred frequencies, and varying stopping patterns. The model is described in more detail in [1]. The models has been used to analyze different possibilities regarding timetables such as merging of lines and decreasing turn-times at terminal stations. However, the model contains a hard-coded network structure, and in an ongoing project an alternative model based on the more general PESP [2, 3] modeling concept is investigated.

2.2 Robustness of Timetables

The daily operation of the trains almost never follows the plan in all details. Minor and major disturbances occur over the day. It is vital that these disturbances influence the service level as little as possible. The first step in this direction is to ensure that timetables are robust. However, there is a trade-off between robustness and cost. Therefore S-tog in collaboration with software vendors and consultant companies has developed two simulation models capable of analyzing both existing and new timetables, [4].

Both models use the general simulation software ARENA, which allows for varying levels of detail regarding the network infrastructure and the rolling stock and crew plans used in the simulation. Constructing a model based on the railway simulation software RailSys is currently under consideration.

2.3 Challenges

Even though it is easy to observe that a timetable is not robust when it is used either in operation or in a simulated situation, it seems to be difficult to define properties which when present lead to a robust timetable. Furthermore, robustness always comes at a price. Hence it is very important to develop concepts and tools, which allow for a quantification of the price of robustness. Such a quantification will require either that new theoretical concepts are developed and demonstrated to be valid, or the use of simulation tools to evaluate the properties of the timetable in operation. The latter in turn requires that crew and rolling stock plans are developed in sufficient detail, and that O-D matrices with reliable estimates for passenger numbers are available.

3 Rolling Stock

One of the first applications of mathematical programming techniques in PPA was the development of a model for evaluating the need of rolling stock in a given timetable and for given passenger demands, cf. [5]. The objective of the model is to minimize both the number of rolling stock units and the number of kilometers driven by these, while maintaining a given standard for passenger comfort. Based on the results from the model, the number of train units was reduced with 12 % and the number of kilometers with 13 % without any measurable effect on the customer satisfaction (measured twice a year).

3.1 Operational Conditions

As mentioned in the introduction, S-tog currently has 104 1/1-units and 31 1/2-units. The units can be combined to various train sizes. All combinations resulting in sizes from 1/2 unit to 2 1/1 unites except the one consisting of 4 1/2 units are possible.

In the early morning hours, the number of passengers is limited. During the morning rush hour, the number of passengers peak, however, in general the passengers travel towards the city center. Consequently, excess seat capacity on trains from the city center towards the outer terminal stations is present. After the morning rush hour the number of passengers decreases. During the evening rush hour the number of passengers increases, although not to the level seen in the morning. Here, the passenger flow is towards the terminals. At the end of the day, the number of passengers again decreases.

Hence an optimal plan for rolling stock circulation calls for several changes in train compositions: Two changes to increase seat capacity, and two to reduce seat capacity. Such changes are carried out at the rolling stock depots.

When not in use, the train units are either parked in rolling stock depots or taken out for maintenance. The rolling stock depots are in general located at the terminal stations of the network, but a large depot is also located at Copenhagen Central. The depots at the terminal stations are of varying size. Hence it may from a train parking point of view be impossible to implement an otherwise feasible rolling stock circulation. The maintenance station is located in Høje Tåstrup.

The driving activities in relation to shunting are handled by a special category of personnel adding additional complexity to the process of deciding whether a given rolling stock plan is implementable from a depot point of view.

3.2 Tools for Rolling Stock Optimization

A plan for the circulation of rolling stock has to take into account a number of conflicting objectives: Almost all passengers should have a seat while the number of train units necessary to cover the operations should be kept low and the number of kilometers driven by these should be minimized. In addition, the plan must include possibilities for maintenance, and should be robust against disturbances.

The general approach for this type of planning is the one also used in the airline industry: Anonymous rotations are constructed based on the departures defined through the timetable and on the expected passenger numbers on these. Close to the day of operation, physical train units are then assigned to the different train numbers of the operation.

S-tog is together with a software vendor currently in a system development process aiming at producing optimization software capable of performing rolling stock planning. The basic structure of the system resembles that described in [6]: First, the so-called composition problem is solved to find the best combination of train units for serving the timetable with the estimated number of passengers. After that, the rotation problem is addressed, i.e. it is determined whether it is possible to assign physical train units to the suggested composition, respecting constraints regarding maintenance, depot capacities, and shunting possibilities.

The model for the composition problem is a large-scale integer programming model, the result of which is used as input for the rotation problem. The rotation problem is solved using Branch-and-Price. One possible result is that no feasible rotation exist for the current composition - in that case the composition problem is resolved with the inclusion of constraints making the current solution to the composition problem invalid.

The model and software is expected to lead to substantial savings as well as to enable faster development of plans.

3.3 Disruption Management and Recovery

When a severe disruption occurs, one of the possibilities used by S-tog is to cancel all trains on one or more lines or "half-lines" in the network, i.e. to change to a frequency of 20 minutes. In practice, the trains on an affected line are taken out as they pass the depots and are parked there for later re-insertion. Since the major part of the lines all pass the central section, the congestion caused here by the disruption is alleviated, and the potential for "returning to plan" is dramatically increased.

Having recovered form the disruption, the canceled lines are then to be re-inserted. S-tog has developed in-house software to ensure the optimal re-insertion of the trains on the canceled lines. This problem is non-trivial partly because the train drivers of the canceled trains are transferred to the crew depot at Copenhagen Central (from where drivers then have to be transferred back to the rolling stock depots), and partly because of the company rules applying to the re-insertion procedure. For example, if a canceled line starts servicing a station by a particular departure, all succeeding departures from that station on the line must also be serviced. A detailed account of the problem and model is given in [7].

The activities in relation to disruption management and recovery are carried out as activities in an industrial Ph.d.-project aiming at producing a prototype decision support system for rolling stock dispatchers at S-tog.

3.4 Challenges

The optimization of rolling stock plans is well understood. In the S-tog context the challenge here is that constraints regarding shunting movements are composed of both constraints regarding the physical layout of depots, and constraints regarding the manning of these. The first issue has been addressed in [8]. The challenge regarding the second is to avoid the necessity of human interaction in evaluating whether a given rolling stock plan is feasible from a shunting point of view. The undergoing rolling stock system development addresses this question.

4 Crew

4.1 Operational Conditions

S-tog employs approximately 550 drivers. The daily schedule of a driver is a so-called duty. Such a duty is either a pre-planned sequence of driving tasks or a stand-by duty. Each individual duty is composed by tasks - mainly driving tasks.

Each task is in general either driving from Copenhagen Central to a terminal station and back (half a round) or a full round on a line. The duties are organized in rosters. A roster is a set of week-plans for an even set of weeks, and is covered by a corresponding number of drivers in a rolling fashion. Of the 550 drivers, 350 are assigned to pre-planned rosters and 200 are stand-by drivers.

The general structure of a duty follows one of two templates: Check-in, drive task, break, drive task, and check out, or check-in, drive task, break, drive task, break, drive task and check out. If the duty has only one break, this has to be at least 30 minutes. In case of two breaks, the total time must be at least 45 minutes and each break must be at least 20 minutes. The duties also include walking time between platform and break facility.

A duty has to comply with many types of rigid rules as e.g. constraints on maximum working hours and minimum break hours. Furthermore, it is necessary to take into consideration many essential features for the entire set of duties in a plan, e.g. the average working hours for all duties, the average working hours in late duties and the variation of tasks in duties.

The pre-planned rosters are of varying size from 8 weeks up to 32 weeks. An 8-week roster consists of legal daily duties combined in such a way that the complete roster respects all safety requirements and union agreements regarding e.g. number and pattern of days off and average number of working hours. 8 drivers are assigned to the roster and perform the duties iteratively such that each driver in turn takes each of the 8 weekly working patterns.

In order to make efficient use of the driver resources, driving tasks must first be combined to efficient duties, and these duties must then be combined to efficient rosters. Efficient in this context means that the number of hours in each duty spent in the driver seat of a train must be as large as possible. Very efficient duties and rosters on the other hand contain little slack and plans based on these are hence very sensitive to disruptions in the daily operation. Experience shows that disruption occurs so frequently that an optimal plan for a situation without disruptions may be considerably more expensive in operation than a less efficient plan, which includes slack.

In Figure 2 the percent-wise development in efficiency of duties and rosters after the introduction of advanced software tools is indicated. The results clearly demonstrate the potential of the methods. However, it is expected that the current level of efficiency is close to optimal due to that duties must contain time not spent on driving (e.g. check-in and -out and meal break).

4.2 Planning Tools

The crew planning in DSB S-tog is based on two systems: TURNI [9] which is the system used to construct the driver duties, and CREWS [10], which is applied for short term scheduling and for maintaining all relevant information regarding each individual driver. Both systems are of course tailored to the specific rules and agreements regarding working conditions as well as other internal requirements.

TURNI is a system based on mathematical programming. The underlying model is a Set Covering model, and dynamic column generation, Lagrangean

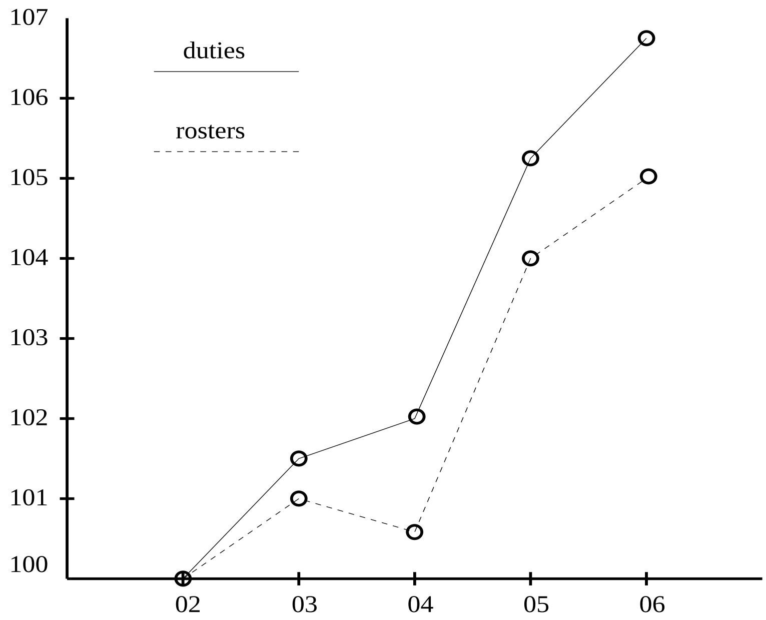

Fig. 2. Development in efficiency of duties and rosters achieved after the introduction of IT-based planning tools in S-tog

relaxation, and heuristic search are applied in the solution process. Each column corresponds to a duty satisfying the S-tog specific constraints regarding breaks etc. The system is a stand-alone system in that no other optimization software is necessary (as e.g. an LP/IP-solver like CPLEX). The system offers insight into the optimization process in that feasible solutions to the duty generation problem are available throughout the process. The user interface of the system is not advanced, and hence the use of the system requires some skill of the planner working with it. Adjustments of rules and regulations are possible, but in general this requires consultant assistance from the software vendor. TURNI allows for the setting of a large set of parameters as e.g. maximum no. of duties exceeding a specific limit, amount of slack time added in connection with breaks, and maximum working time after 17.00. Since the parameters are not mutually independent it is a non-trivial task to choose an appropriate setting. In this context, classical statistical experimental design has been applied.

TURNI in general produces a very efficient set of duties. These duties are through a process with interaction between management and trade union representatives partitioned into rosters. Drivers are finally assigned to rosters according to a bidding scheme based on strict seniority.

The crew assignment including duties and rosters are then fed into S-tog's version of CREWS (called PDS), which is used for manual short-term scheduling. PDS has an advanced user-interface making the system generally accessible for crew planners, however, the system has no on-line data access and no decision support for use in case of disruptions. PDS also contains a module for duty generation. S-tog, however, for various reasons currently maintains the use of TURNI for this task.

4.3 Estimation of Crew Demand

For the estimation of crew demand, S-tog has developed an integer programming model based on the workload profile representing the required rolling stock for the public timetable, and on a number of templates representing standard working days for drivers - so called duty templates. The output from the model is an estimate of the number of drivers needed and a distribution over the day of the check-in times of the drivers. The objective for the model is to minimize the number of duty templates (equal to number of drivers) necessary to cover the workload profile. Other possibilities are minimizing the total amount of working hours. The model implements a number of union rules directly by constraints or through the input. During the estimation no actual crew rosters are built. The model is described in [5].

A number of settings can be changed in the model. Besides the level of time discretization in the input, a number of constraints representing specific S-tog requirements such as required number of average breaks, required number of special duty templates, and gap tolerance have been implemented.

TURNI not only gives the number of drivers but the precise working schedule for all drivers needed to cover a specific workload, and thereby the public timetable. When knowing an exact rolling stock plan, there is hence no need for estimates since exact results can be obtained. However, the estimation model can be used if only a rough estimate of the rolling stock is available (i.e. early in the complete planning process). Also, the model can be used for other groups of personnel as e.g. ticket inspectors. The duties of these are significantly different from driver duties. With such a model we will be able to estimate the required amount of ticket inspectors covering a desired workload profile, and to decide their check-in time during the day. The model is currently under development, the aim being to increase the control frequency on lines and times of day, where experience shows that most passenger travel without valid tickets.

4.4 Robustness of Crew Plan vs. Timetable

The simulation model SiMS currently under development simulates the circuits of trains, and the process of covering each departure of the S-tog network with drivers. Drivers are available at crew depots only. SiMS is basically run on the tasks given by the crew plan. The trains are running in circuits according to the train sequences. In the model they are implemented as transporters picking up drivers as specified in the duties of these. In that way, the departures given by the timetable are covered.

As a train can only run in operation when a driver is present, simulation of the covering of train-tasks is included. For this purpose, reserve drivers are available in a predefined schedule over the day. Tasks are covered by employing a set of dispatching rules that prioritize the use of vacant scheduled drivers over using reserve drivers. One dispatching rule is the swapping of tasks among drivers to cover more tasks in total. If no possible solution is found, an imaginary driver is used for covering the task. An imaginary driver is equivalent to an extra reserve. In real-life the train is canceled if no vacant scheduled driver or reserve driver can be found.

SiMS enables the quantification of robustness of the crew plan with results such as punctuality, employed reserve and imaginary drivers, and violation of work rules. This in turn facilitates evaluation of timetable proposals and/or crew schedules.

4.5 Disruption Management

S-tog daily faces disruption of the operation in terms of both minor and major incidents. Currently, the handling of disruptions is based on a set of experienced crew dispatchers. The dispatchers have IT-support in terms of access to drivers duties and overview information regarding the status of the operation (e.g. current delays of trains in the network). However, there is no integration between the different information systems, and there is no decision support to change driver duties.

On average, the punctuality of the operation is close to the 95 % aimed for in the traffic contract. The punctuality in the rush-hours are substantially lower, whereas the punctuality outside rush-hours are higher. This is of course unfortunate since the major part of the passengers travel during rush-hours. Therefore, its is a current focus issues of the company to improve punctuality. Currently, no suitable software product on the market is available, and in addition the lack of integration between different internal IT-systems is a substantial problem.

A prototype decision support system for train driver dispatchers is currently under development as a part of a Ph.D.-project supported by S-tog. A solution method to the Train Driver Recovery Problem, described in [11], is based on rescheduling a small part of the train driver schedule affected by a disruption. The problem is formulated as a Set Partitioning problem and possesses strong integer properties.The proposed solution approach is therefore an LP-based Branch & Bound algorithm.The LP-relaxation of the problem is solved with a dynamic column and constraint generation algorithm. Pilot experiments are very promising, both with regards to the integrality property and to the efficiency of the method.

The main objective is to minimize the number of changed duties. The main goal is to avoid the communication problem resulting from a large number of duty changes, since the communication has to be performed manually by the crew dispatcher. A second objective is to produce a robust plan, where robustness is defined as large buffer times before breaks within the recovered duties. The main focus in the project is cancellations of entire train lines for a period of time, which is commonly used to alleviate larger disruptions.

4.6 Challenges

The process of crew scheduling is currently automatic except for the construction of rosters based on the generated duties. Roster generation is a problem very similar to duty generation, and hence similar methods are expected to be applicable.

The major challenge in connection with crew is disruption management. This will first of all require data integration, and secondly the development of on-line rescheduling methods. Currently it seems feasible to build upon solution methods in use for generating the crew plans. The introduction of such a decision support system is crucially dependent on accept from the crew dispatchers, and although the first steps have been taken, there is a long way to go. Also issues regarding system integration with the passenger information system are pending.

5 Challenges with respect to Integration

The planning schedule in S-tog is currently sequential according to existing traditions: First timetable design, the rolling stock planning, and finally crew planning. The use of IT-based tools in all phases opens the possibility of overlapping phases and of iteration. The effect will be a substantially shorter planning cycle, which in turn enables "what-if" analysis.

Another type of integration is the integration of planning of other resource areas as e.g. maintenance. Efficient maintenance is necessary to make best possible use of the available equipment. Today, the planning of maintenance is separated from operational planning. A future challenge is to allow for integrated planning thereby allowing more efficient use of the rolling stock available.

If the results from the prototype work with recovery systems for drivers and rolling stock are promising, the next step regarding disruption management is to investigate the possibility of integrated recovery for these resources.

6 Paving the Way for Optimization - Organizatorial Issues

As is apparent from the preceding sections, the use of decision support and planning systems based on IT and mathematics is not restricted to a single planning area like rolling stock or crew. This is often the case in larger companies: Such tools are used in some part of the organization but not in others. Experience from PPA shows a number of good reasons for tools to be part of the planning process, and for the presence of a special section in the department responsible for analysis of the daily operation, for knowledge of the tools used in the planning, and for maintaining technical insight into the mathematics and algorithms on which the tools are based.

The key reason is purely economical: Using advanced tools eventually lead to a more efficient operation, and furthermore alleviates the risk of "tacit knowledge" disappearing from the company in case key employees leave the organization. Even an efficiency enhancement of a few percent per year is for a larger company enough to cover the extra expense in terms of salary for analysts and software costs.

Other reasons include the problem insight developed by being forced to explicitly express all rules of a planning process. Here, new ideas emerge, and procedures based on current practice are questioned by experiments with new tools. Also, the potential for "what-if"-analysis plays an important role.

From an organizatorial perspective, the single most important factor in accepting advanced tools as part of the general planning procedures is personal support. There has to be an understanding of the potential and impact of changing planning procedures to include more sophisticated methods and analysis tools on all levels of the organization. At least one person has to accept the role of "champion" for introducing mathematics, IT, and employees with a different background. This has been the case in S-tog, and experiences from other applications support the observation.

On the other hand, academic employees have to prove their worth. If the tools and methods introduced in the organization do not match the requirements of the planners either in terms of functionality or in terms of user interface, the chance of success is small. Also, the first applications must prove the value of the approach in terms of cost decrease or profit increase.

To survive in a longer perspective, it is furthermore necessary for an analysis section to be visible with regards to daily activities. This requires the identification of and development of new application domains as well as a willingness to support the the daily operation. New application domains may also relate to strategic development of the company both with respect to products offered to their customers and with respect to extending the scope of the company's activities.

The above discussion illustrates the trade-off often experienced in connection with research and applications in mathematics and IT. Researchers often focus on concepts, theory, and methodological development, whereas companies are interested in the direct application potential of the research. There is a substantial risk that the two parties do not understand each other, and even worse, after a while do not see any reason to pursue collaboration. This dilemma is also apparent in the railway optimization context. Although changes do not happen overnight, the experiences from S-tog is that it is not an impossible task to make an organization acknowledge the value of research and make researchers appreciate the practical use of their efforts.

7 Conclusions

The planning of timetable, rolling stock and crew in S-tog to meet requirements of service, efficiency, and robustness is a challenging task integrating three business areas, each of which is in itself highly complicated. Traditionally, plans are made by highly qualified persons with many years of experience in planning and running the daily operation of the business.

Due to the complexity of the problems at hand it is very likely that the manually constructed solutions to the planning problems can be improved, and that improved efficiency may result from new ways of running the operation. For S-tog, software with optimization capabilities has proven to be an indispensable tool for the planners to obtain even better plans, to analyze "what-if" scenarios in relation to current plans, and to investigate new ideas.

Future perspectives of using OR methods in S-tog include combined maintenance and production planning, and real-time decision support for re-planning of crew and rolling stock in the event of disruptions. Also, improving the robustness of plans regarding their sensitivity to both larger, planned changes (as track reconstruction), and the disruptions and delays observed in the daily operation are key issues.

References

1. M. N. Nielsen, B. Hove and J. Clausen: Constructing Periodic Timetables using MIP - a case study from DSB S-train. International Journal of Operations Research **1** (2006), 213 – 227.
2. P. Serafini and W. Ukovich: A Mathematical Model for Periodic Scheduling Problems. Siam J. Discrete Mathematics **2** (1989), 550 – 281.
3. J.C. Villumsen: Construction of Timetables Based on Periodic Event Scheduling. IMM-Thesis-2006-52 (2006), Informatics and Mathematical Modelling, Technical University of Denmark.
4. M. A. Hofman, L. Madsen, J. J. Groth, J. Clausen, and J. Larsen: Robustness and Recovery in Train Scheduling - a simulation study from DSB S-tog a/s. IMM-Technical Report-2006-12 (2006). Informatics and Mathematical Modelling, Technical University of Denmark.
5. M.N. Nielsen, J. Jespersen, and M. Folkmann: Estimates on Rolling Stock and Crew in DSB S-tog Based on Timetables. Lecture Notes in Computer Science **4359** (2007), 91 – 107.
6. P.J. Fioole, L. Kroon, G. Maroti, and A. Schrijver: A rolling stock circulation model for combining and splitting of passenger trains. European J. of Operational Research **174** (2006), 1281 – 1297.
7. J. Jespersen Groth, J. Clausen, and J. Larsen: Optimal Reinsertion of Cancelled Train Line. IMM-Technical Report-2006-13 (2006), Informatics and Mathematical Modelling, Technical University of Denmark.
8. P. Føns: Decision Support for Depot Planning in the Railway Industry. IMM-Thesis-2006-42 (2006), Informatics and Mathematical Modelling, Technical University of Denmark.
9. E.J.W. Abbink, M. Fischetti, L.G. Kroon, G. Timmer, and M.J.C. M. Vromans: Reinventing Crew Scheduling at Netherlands Railways. Interfaces **35** (2005) , 393 – 401
10. Siscog home page: http://www.siscog.pt/
11. N.J. Rezanova and D.M. Ryan: Solving the Train Driver Recovery Problem. IMM-Technical Report-2006-24 (2006), Informatics and Mathematical Modelling, Technical University of Denmark