Optimal Reinsertion of Cancelled Train Line

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Abstract

DSB S-tog (S-tog) is the operator of the suburban rail of Copenhagen, Denmark. The suburban network covers approximately 170 km of double-track and 80 stations. When larger disturbances occur in the S-tog network one of the countermeasures is to take out entire train lines. The problem is to decide when the reinsertion shall start on each rolling stock depot in order to resume scheduled service. As the process of resuming service is regulated by a number of constraints, the task of calculating a reinsertion plan of a train line becomes complex. Here we present a mixed integer programming (MIP) model for finding a reinsertion plan of a train line minimizing the latest time to reinsertion. The MIP model has been implemented in GAMS and solved with Cplex. The optimal solution is found within an average of 0.5 CPU seconds in each test case. Reinsertion plans in operation is today calculated by the reinsertion model.

1 Introduction to DSB S-tog

DSB S-tog (S-tog) is the operator of the suburban rail of Copenhagen, Denmark. The suburban network covers approximately 170 km of double-track and 80 stations. Daily the operator transports approximately 30.000 passengers. S-tog is the only user of the tracks, which are controlled by the infrastructural owner BaneDanmark (BD).

The S-tog network consists of train lines covering the S-tog infrastructure by various compositions of routes depending on the timetable in use. Figure 1 shows the present lines in the network. The network can be thought of as consisting of 8 sections; A central section, 6 fingers, and a circular rail. The lines merge in the central section, and they split as they re-enter the fingers according to their schedule.

The structure of the S-tog network implies that a high number of lines intersect in the central section. The trains on each train line run with a frequency of 3 trains per hour which means an frequency period of 20 minutes. Given 10 lines intersecting the central section this means that within 20 minutes there is on average only 2 minutes between each train in the central section i.e. there is a 2 minutes average headway in between the trains. Such low headway implies that even small delays can have a significant negative effect on a high number of trains.

Each line in the S-tog network is covered by 4 to 10 trains depending on the duration of the line circuit. This is the time it takes for a train to drive from one terminal to the other terminal and back. The duration of a circuit and the time planned for turnaround at the terminals divided by the frequency period (20 minutes) gives an integer, which is the number of trains required to run the line. Each train consists of one or more train units i.e. the train units are the physical units covering the virtual train running. The composition of a train varies during the day according to the expected passenger demand.

At all times a train number is associated with each operating train. The train number is changed every time a train turns at a line terminal to run in the opposite direction. For each train there is hence a series of train numbers during the day defining the train tasks of that particular train. A train tasks is a departure departing from terminal s_1 at time t_1 and arriving at terminal

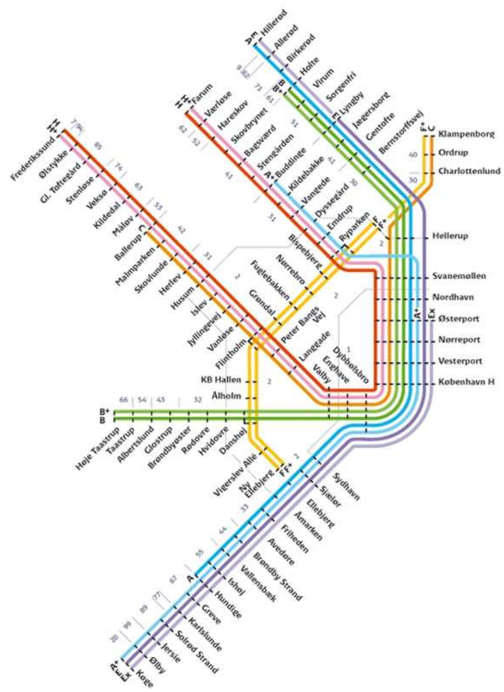

Figure 1: The network of DSB S-tog in 2006

s_2 at time t_2. The number series of a train is called the *train sequence* and there can be only one train sequence for each train. Also, two train numbers cannot occur in two different train sequences. Figure 2 shows an example of a line covered by two trains where each train is covered by a train sequence and different train units during the day. The breach on the bottom train illustrates that all train units on the train are exchanged with new.

At S-tog there is much information embedded in the train numbers. Each train number identifies the present train line, stopping pattern, direction (north/south) and an time interval of arrival at KH for a train. The time interval is given by the two last digits in the train number e.g. if these are 35 the integer part of a division by 3 indicates that the train arrives at hour 11. The remainder, which is 2, indicates that the train arrives at the 3rd frequency period within that hour. For two train numbers on the same train line, the train number with the lowest value of its two last digits will be the

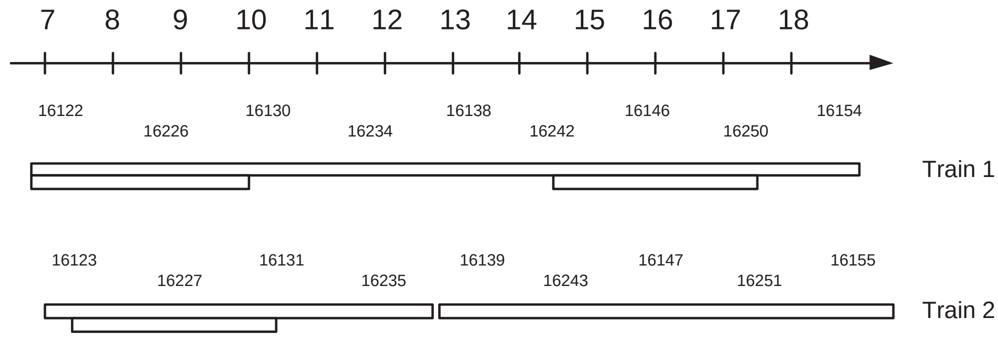

Figure 2: Two train series together covering the two trains on a train line (here represented by the train numbers). Each train number indicates a train task for the train. The drawn up lines illustrates train units covering the task. When two drawn up lines cover the task there are two train units assigned to the task. The Thickness of the lines represents the number of train units needed. So for both trains two units are needed in the morning rush hour. Only train 1 consists of two units in the afternoon.

train task performed first. For two adjacent train numbers in the same train sequence there is a constant interval between the values of the last two digits.

Rolling stock depots are placed at the most of the line terminals and at the central station. The only crew depot is located at the central station. When trains are started up at a rolling stock depot, the required crew is transported from the crew depot. Trains are inserted and taken out in the network from the rolling stock depots.

In this paper we will address the problem of reinserting a cancelled train line. In the Reinsertion problem trains are handled virtually i.e. the track routes used when driving the trains from depot to platform are assumed to be known also the decision of which platform to use at a depot is not addressed i.e. the departing platform is also assumed known.

The remainder of the paper is organized as follows. In Section 2 we describe some of the recovery strategies used at S-tog and the process of taking out trains when cancelling a train line. In Section 3 the Reinsertion problem is described. In Sections 3.2 and 3.3 the input for the problem is described and an example is given to clarify. In Section 4 a mixed integer programming model for the reinsertion problem is described. Computational results are presented in Section 5. Section 6 describes the initial background for formulating a mathematical model for the problem. Finally potential further developments are described in Section 7 and a conclusion is given in Section 8.

2 Recovery Strategies

During the daily operation incidents occur that disturb the scheduled departures. One way to compensate for potential disturbance is to construct timetable and, crew and rolling stock plans with included buffer times. For example, in the timetable buffer times can be included in the headways, the dwell times on stations and as a part of the turnaround tunes. In the crew plan an example of buffer times can be extra time included around breaks. It is not necessarily evident where in the schedules it is optimal to allocate the buffers. This information can be derived by e.g. simulation studies based on real observations of the schedules, c.f. Hofman et al. [2].

Even though precautions are taken to minimize the effects of incidents, it will not be possible to avoid delays completely. Therefore, different recovery strategies have been developed for recovering the timetable and, the crew and rolling stock plans. Examples of recovery strategies at S-tog are

- *Turning trains earlier on their route* (see figure 3)
- *Train planned to stop at all stations can be made a non-stop train on smaller stations*
- *Cancellation of entire train lines*

An example of early turnaround is illustrated in Figure 3. Normally, a train on line A drives from Køge to Hillerød. Because a unforeseen delay has occurred on the first part of the route, it is decided by the dispatchers to turn the train around early in Lyngby. In this way the stations on the route between Lyngby and Hillerød are skipped.

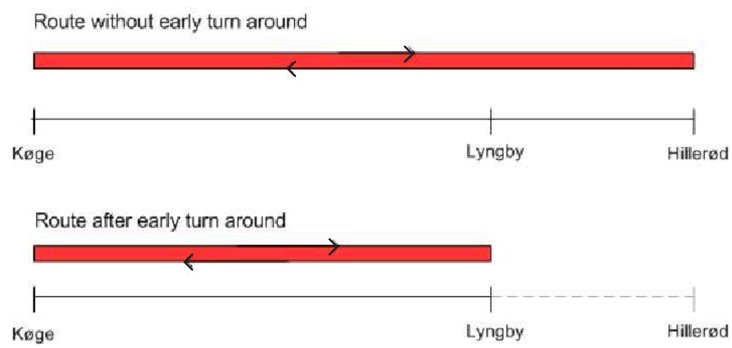

Figure 3: Illustration of an early turnaround

Managing recovery is a joint task for the infrastructural owner and the operator using the tracks. In the S-tog network BD has the responsibility and the authority of the departures. S-tog has at its disposal the resources crew and rolling stock and has therefore the responsibility of matching these resources to the demand defined by the departures.

When larger disturbances occur on the S-tog network, the disturbance is often redeemed by taking out an entire train line i.e. all departures on a train line are cancelled. By taking out a train line more slack is created in the timetable, i.e. the headways are increased between time adjacent train lines. This creates increased buffer times in the timetable and more room is created for absorbing the delays.

A cancellation of a train line is implemented by shunting the rolling stock to depot tracks as the trains arrive at rolling stock depots. In the process of cancellation it is normally not allowed to drive "backwards" in the network i.e. driving a train in the opposite direction of what it was originally planed to drive. A train can only move forward to the next depot where it will be taken out of service. Therefore, the trains on the cancelled train line ends up being distributed among the depots along the line according to where they were in the network when the decision of cancelling the line was made. It is crucial to realize that train units that are taken out at a depot are not necessarily used to cover the same trains when reinserted. Recall that a train is defined by its train sequence and not by the train units covering it.

3 The Reinsertion Problem

When an adequate level of regularity has been re-established in the operation, the cancelled train lines should be reinserted according to the original timetable. The status of operation is evaluated by a train controller from BD. After the decision of initiating reinsertion has been made, the reinsertion should be carried out as quickly as possible.

When a train is reinserted it is transported as empty stock from the depot tracks to a platform. A train driver arrives on a operating train from the crew depot at the central station (KH). The train to be reinserted departs according to a scheduled departure on the relevant train line.

For the reinsertion problem it is assumed that train units will be shunted to departing platforms according to standard shunting times and available track routes. Relevant to the problem is "only" to assure that all trains are inserted at some depot on the train's route.

The reinsertion plan is calculated by a rolling stock dispatcher from S-tog. The reinsertion is presently computed for one train line at a time. It is necessary to decide which trains already in operation can transport train drivers to the rolling stock depots, from where the trains are inserted. The number of trains to be inserted from each depot is determined by the dispatcher, however, it is not given which train units at the rolling stock depots should be inserted to cover which trains in the schedule of the train line.

For most lines, intermediate rolling stock depots exist along the route of the line. As for the terminal depots, it is determined, prior to the calculation of a reinsertion plan, how many trains must be inserted from the intermediate depots in total. At an intermediate depot trains can be inserted in both directions. Inserting in both directions decreases the finishing time of the reinsertion process. This is because of the double track network. Two departures in opposite direction are not bound by headways as there is generally not interdependency between the infrastructure going north respectively south. Therefore, when inserting in both directions on an intermediate depot the total time of insertion can be reduced. For example, three trains must be inserted from a depot. Departures going north are at minutes 03, 23 and, 43 every hour. Departures going north are at minutes 06, 26 and, 46 every hour. If all trains are inserted in one direction, the reinsertion will span over 40 minutes. If the trains are inserted in both directions, the reinsertion will span over just 20 minutes.

In the reinsertion problem each train must be reinserted only once also the number of trains reinserted in each time slot for a depot must be covered at most once. Finally, it is given for each depot exactly how many trains must be inserted.

The reinsertion must be made under two different considerations of order. Firstly, if reinsertion has begun from a given rolling stock depot, the remaining trains to be inserted from that depot must be inserted in order according to the frequency period. For example, at S-tog the frequency period is 20 minutes on all train lines. If 3 trains must be reinserted from Farum rolling stock depot and the first reinserted train departs at 15:18, then the remaining 2 trains must be reinserted and depart at respectively 15:38 and 15:58. Inserting the remaining two trains at 15:58 and 16:18 would mean an unassigned frequency interval at 15:38 i.e. order would not have been kept and that would be an illegal solution. Secondly, the order with respect to frequency must also be kept across rolling stock depots. That is, after the initiation of reinsertion, the time between two adjacent departures on any station in the network must always be the frequency period of 20 minutes.

One of the advantages of the reinsertion model is the solution time of the model compared to manual calculations. Also, it is possible to calculate a reinsertion plan immediately when the distribution of trains among depots is known after the take out. As the timetable is periodic the reinsertion plan calculated will in principle be the same except for the exact train numbers that must be inserted. This might lead to some advantages with respect to coordinating the train driver schedules according to the reinsertion, thereby preventing reinsertion schedules being discarded because of the lack of drivers.

3.1 References

Recent surveys on rail operation models are given by Cordeau 1998 [1], Huisman et al 2005 [3] and Törnquist in 2006 [4]. The reinsertion problem and models for solving it is not mentioned in either of these surveys. A thorough search has not produced any additional literature that resembles the problem of reinserting train lines. The problem seems to be specific to the Copenhagen suburban network.

3.2 Input to the reinsertion model

The reinsertion problem can be solved given relatively little information. There are two types of input necessary in the model: input based on background data and input based on real time data. Firstly, the model must be built with background data based on the timetable structure. Secondly, after the construction of the model certain input in real time is necessary for deriving the right reinsertion plan according to the relevant real time scenario.

When building the model it is essential to know for each depot how many cancelled departures there are from the time of decision of reinsertion and until the first driver can arrive and be ready for driving the first potential reinserted train, see Figure 4. The time of decision of reinsertion is always coinciding with the departure of train from KH, which can carry drivers to the reinsertion depots. Furthermore, it is necessary to know the number of trains on the train line. As mentioned in Section 1, each train can be viewed as a sequence of train numbers. Due to the periodic format of the timetable the solution to the reinsertion problem is generic i.e. the structure is independent of the specific times given in the timetable. Therefore, when building the model, it is only necessary to be able to differ between the trains. It is sufficient to make one calculation for each distribution of trains over depots. As there is only a limited number of possible distributions of trains among depots, all solutions can in fact easily be generated in advance and updated according to time of day in the real time situation. Knowledge of exact train number to be reinserted are not relevant before real time.

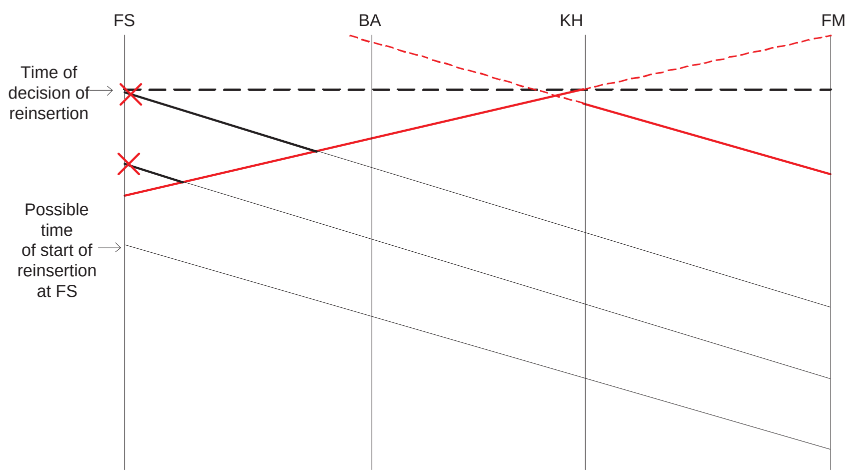

Figure 4: Illustration of the reinsertion start time at the FS depot. From the decision of reinsertion until the reinsertion can begin at the FS depot, the two first train with scheduled departures after the time of decision of reinsertion cannot be reinserted as the train carrying drivers has not yet reached the depot.

In real time the necessary input are the trains distribution among the depots and which operating train number is the first that can carry out drivers to the depots. For the latter, it is only necessary to give as input the train going in one of the directions as the train in the other direction can be derived. The specific train numbers to be inserted can also be derived from the train number given as input and the reinsertion solution, which can be looked up from the distribution of trains among depots. Additionally, the train numbers that will be used to transport the train drivers to the rolling stock depot must be identified. These can also be derived from the reinsertion solution and the input train number. Summing up, the solution looked up by the rolling stock dispatcher is used to find the train numbers of respectively the trains to be reinserted and the trains to transport drivers.

3.3 A real life example

To illustrate the reinsertion problem we give an example of a reinsertion. Two lines, H and H+, run on the route between Frederikssund (FS) and Farum (FM). When large disturbances occur involving the sections of this route, the H+ line is typically taken out. The 10 trains servicing the H+ train line are taken out on the terminal rolling stock depots, FS and FM, and on the intermediate depots at Ballerup (BA) and KH. Recall that the crew depot is at KH. In this example, 2 trains are taken out on each of the terminal depots and 3 on each of the intermediate depots. One scenario of reinsertion is then that reinsertion is carried out, exactly according to the take out, in which case 2 trains must be reinserted from each terminal depot and 3 trains must be reinserted from each intermediate depot where insertion is possible in both directions. If extra train units are available on any of the depots several reinsertion scenarios are possible according to how many units are available and at which depots.

Figure 5 illustrates the trains that are available for transporting drivers. Train a and d are the first trains going respectively south and north that can bring out drivers to depots. As these trains pass the depots in each direction, the reinsertion at those depots can be initiated i.e. potential drivers are now available for reinsertion.

In the reinsertion model the initiation time of reinsertion on each depot is counted in integral time slots according to the frequency period within the timetable. It is counted how many trains on the train line in question was planned to leave the depot from the decision of reinsertion until the first driver-carrying train reaches the depot. In Figure 4 there are 2 trains

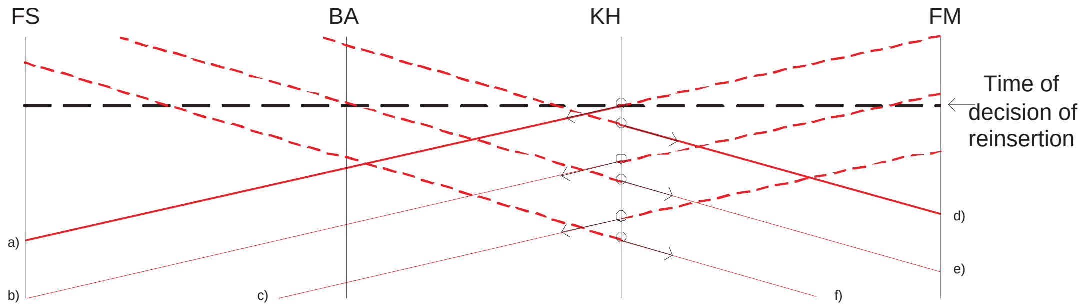

Figure 5: The straight lines a, b and c illustrates trains carrying drivers going south and the lines d, e and f those going north. The lines initiate reinsertion at the different depots as they pass them.

originally planned to leave the FS depot before reinsertion can begin. Notice that the time of decision of reinsertion is coinciding with the departure time of the first south going train being able to carry drivers. Formally, this is always the case.

The exact approach of a reinsertion is illustrated in Figure 6. For each of the figures a) - d) trains are inserted from a depot. Observe that order is kept at all time. There is no vacant frequency periods at depots and there are no stations where passengers experience vacant frequency periods. Illustrated in red on a), b) and d) is the driver-carrying trains transporting drivers for the reinsertion.

4 The Reinsertion Model

Let I be the set of train that must be inserted and K the set of depots they can be inserted from. J is the set of available slot for reinsertion. The goal of the model is to decide which train, $i \in I$ should be inserted from which depot, $k \in K$. Each originally scheduled train i (before cancellation) must be covered with train units and hence reinserted in operation according to schedule. Also it must be decided for each train in which time slot, $j \in J$,

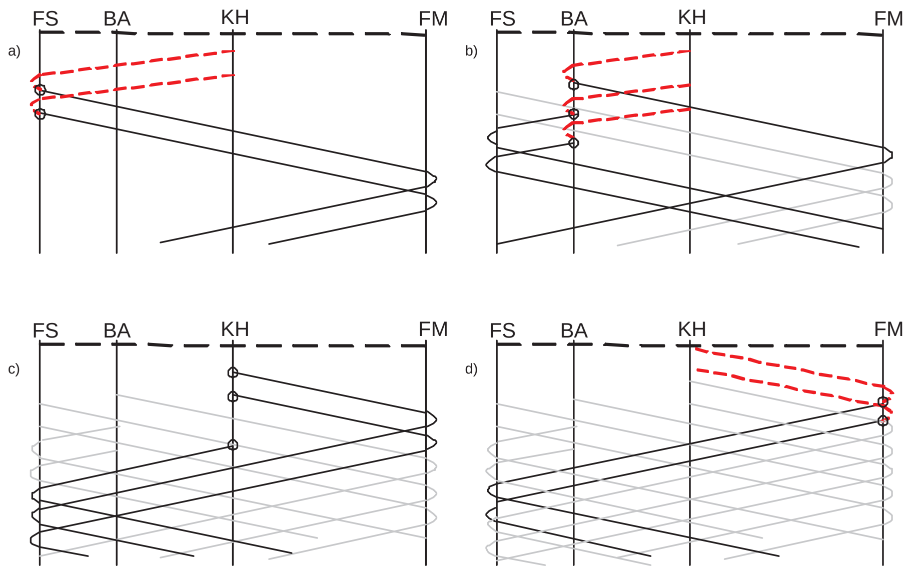

Figure 6: Illustration of a reinsertion. In a) trains are inserted from depot FS, in b) from depot BA, in c) from KH and in d) from FM.

the reinsertion will take place.

The model decides which trains will run but it does not consider which train units to use to cover the trains. It is assumed that the information of distribution of train units across depots, $D_k, k \in K$ is provided as input and thereby sufficient in number to cover the trains.

The variables representing which train to be inserted from which depot and when are binary

$$x_{ijk} = \begin{cases} 1 & \text{if train } i \text{ is inserted in time slot } j \text{ from depot } k \\ 0 & \text{otherwise} \end{cases}$$

Each train must be covered exactly once. This is guaranteed by the partitioning constraints (1)

$$\textstyle\sum_{j,k} x_{ijk} = 1, \qquad \forall\ i \in I \tag{1}$$

Inequalities (2) are included so that no time slot for a depot or train can be covered more than once:

$$\sum_i x_{i,j,k} \leq 1, \qquad \forall\ j \in J, k \in K \tag{2}$$

The number of trains to be inserted from each depot is known. Therefore, binding constraints exist for each depot. They differ for respectively terminal and intermediate depots. As the trains are inserted only in one direction at the terminal depots, $k \in K_T$, the binding constraints for these depots are :

$$\sum_{i,j} x_{i,j,k} = D_k, \qquad \forall k \in K^T \tag{3}$$

As mentioned earlier a better solution can be achieved when insertion on intermediate depots are made in both directions. According to current practise the trains on each intermediate depot are inserted one half of them in one direction and the other half in the other direction. This is handled in the model by including two depots for each intermediate depot. The set of intermediate depots is denoted K^I. It is constructed by sets of two depots together denoting one intermediate depot where reinsertion can be carried out in l directions, $K^I = K_1^I \cup ... \cup K_l^I$, where $l \in L$. L is the set of directions, which in the S-tog network for all depots is north or south. The total set of depots is $K = K^T \cup K^I$. Variables $D_k^I, k \in K^I$ have been added to the model to represent the number of trains inserted each direction.

The sum of trains inserted in both directions should equal the total number of trains to be inserted from the intermediate depot. Equations (4) ensure that the number of trains inserted in each direction is the total number of trains to be inserted divided by 2. If an odd number of trains is to be inserted, the result is rounded up or down to nearest integer depending on which is more favorable to the model.

$$\sum_{i,j,k} x_{i,j,k} = \sum_k D_k, \qquad \forall \qquad l \in L, k \in K_l^I \tag{4}$$

$$\sum_{i,j} x_{i,j,k} = D_k^I, \qquad \forall \qquad k \in K^I \tag{5}$$

$$D_k^I \geq \lfloor \tfrac{D_k}{2} \rfloor, \qquad \forall \qquad k \in K^I \tag{6}$$

$$D_k^I \leq \lceil \tfrac{D_k}{2} \rceil, \qquad \forall \qquad k \in K^I \tag{7}$$

As mentioned in Section 3 order should be kept within depots and between depots. Also, reinsertion must not begin on a depot before a train driver can arrive from the crew depot to drive the train to be reinserted.

To ensure that each train is inserted in an correct time slot, it is necessary to take into consideration the train sequences of each train describing in which time slot each train is at the different depots. To handle this a constant is introduced, $in_{i,j,k}$.

$$in_{i,j,k} = \begin{cases} 1 & \text{if train } i \text{ may depart from depot } k \text{ in time slot } j \\ 0 & \text{otherwise} \end{cases}$$

It is not possible to insert a train from a depot, if it is not there at that specific time slot. We refer to this as the order between stations and it is ensured by inequality (8).

$$x_{i,j,k} \leq in_{i,j,k}, \qquad \forall\ i \in I, j \in J, k \in K \tag{8}$$

Recall that no vacant frequency periods must occur in a solution. To model this, we introduce two sets of integer variables, $start_k$ and end_k. Also, we introduce equations (9) to (12). Equations (9) connect the start and end variables. Equations (10) assure that reinsertion is not begun before the first driver can arrive at the depot. The constant, C_k, indicates how many trains have been scheduled at depot k from the time of the decision of reinsertion until drivers are able to reach the depot, cf. Figure 4. Equations (11) and (12) ensure that when a reinsertion has begun on depot, it is carried out continuously in adjacent time slots.

$$start_k + \textstyle\sum_{i,j} x_{i,j,k} - 1 = end_k, \qquad \forall\ k \in K \tag{9}$$

$$start_k \geq C_k + 1, \qquad \forall\ k \in K \tag{10}$$

$$start_k \leq j + M \cdot \Big(1 - x_{i,j,k}\Big), \qquad \forall\ i \in I, j \in J, k \in K \tag{11}$$

$$end_k \geq j - M \cdot \Big(1 - x_{i,j,k}\Big), \qquad \forall\ i \in I, j \in J, k \in K \tag{12}$$

At S-tog much of the information of the timetable and departures is embedded in the train numbers. The periodic form of the timetable supports this formulation. The train numbers to be inserted when $x_{i,j,k}$ is 1 is calculated from an initial train number on a train able to carry train drivers to the depots and some constant describing the relationship between the train numbers on the driver-carrying line and the line to be reinserted. The train number is adjusted according to the time slot in which it is to be inserted. See equation (13).

$$\begin{aligned} TrainNumber_{i,j,k} = \Big(InitialTrain + TrainConst_k + j\Big) \cdot x_{i,j,k}, \\ \forall\ i \in I, j \in J, k \in K \end{aligned} \tag{13}$$

The objective of the model is to reinsert as quickly as possible. This is assured by an objective function of minimizing the maximum inserted train number, $MaxTrainNumber$. As information of time of day is indirectly embedded in the train numbers this equivalent with minimizing the latest time of reinsertion. This is achieved by minimizing the maximum value of the last two digit number in the train number.

$$Minimize \qquad MaxTrainNumber \tag{14}$$

$$MaxTrainNumber \geq TrainNumber_{i,j,k}, \qquad \forall\ i \in I, j \in J, k \in K \tag{15}$$

5 Computational Experience

The running time of the model is not relevant in real time as reinsertion plans are generated in advance and looked up at the relevant time. Test results

Station	Train	Inserted in time slot:
FS	1	4
KH south going	2	2
KH south going	3	3
BA south going	4	5
FM	5	3
FM	6	4
KH north going	7	3
BA north going	8	2
BA north going	9	3
FS	10	3

Table 1: A solution derived by the model. The first column shows the depot and direction of insertion. The second column shows which of the trains are inserted. The last column shows in which time slot at the depot the train is inserted.

show that the running time of the model on average is only approximately 0.5 CPU seconds, i.e. the model solves the problem in real time for the relevant problem instances. The real time approach is not chosen partly due to software license issues, partly due to the generic nature of the reinsertion plans.

If, for example, $K = FS, BA, KH, FM$ and $D_k = 2, 3, 3, 2$ the optimal reinsertion is as in Table 1.

The practically applicable solution can be derived based on the train number, 50227, the reinsertion solution above and a set of constants. Given that we wish to reinsert a set of cancelled trains starting at 9 o'clock, the first train able to transport drivers south going leaves at 9:08 and has the train number 50227. Also, we assume that the distribution of trains on depots is as above. The practically applicable solution is given in Table 2.

To calculate the train numbers to insert equation 13 is used. For example, for the first row in Table 1 $i = 1$, $j = 4$ and $TrainConst_{FS} = 4902$ which

Station	Train	Train number to transport drivers:	Train Number to insert
FS	1	50228	55133
KH south going	2	Driver present	55228
KH south going	3	Driver present	55229
BA south going	4	50230	55230
FM	5	50127	55231
FM	6	50128	55232
KH north going	7	Driver present	55129
BA north going	8	50227	55130
BA north going	9	50228	55131
FS	10	50227	55132

Table 2: A practical applicable solution. The first column shows the depot and direction of insertion. The second column shows the train number of any driver carrying train. The last column shows the train number to be inserted.

in the first row and last column of Table 2 gives the train number 55133. $TrainConst_{FS}$ is adjusted to give the right direction, line and time of the inserted train number. The train number carrying drivers to the insertion depot is calculated by an equation similar to 13 with other constants.

Each train number indicate a time and a direction. This is sufficient knowledge for the dispatchers to carry out the reinsertion.

6 An Improved Planning Process

The initial request for a tool for calculating reinsertion was made by the rolling stock dispatchers themselves. They regarded the problem of creating reinsertion schedules by hand as complicated and time demanding, especially in real time where time is sparse. First a tool was made that was not based on the principles of MIP. It was merely a spreadsheet calculating the reinsertion plan from basic knowledge of the distribution of trains, the first driver-carrying train and a large set of if-then-else-loops. The project of creating an optimization model for calculating the reinsertion was started mainly due to the quite complicated task of updating the initial reinsertion tool. The mathematical model of the reinsertion problem has been implemented in GAMS and solved in CPLEX. It has been in operation since the August 2006.

Solutions are generated with the MIP model for all possible scenarios of train distributions over rolling stock depots. The solutions are then stored and the rolling stock dispatcher can look up the solutions via a spreadsheet.

The reinsertion model has increased the level of service offered to the passengers. Earlier, when the rolling stock dispatcher had to make the calculation of reinsertion by hand, the solutions where either not generated because it took to long time to calculate a solution, or a solution was generated with a longer total reinsertion time than the optimal solution. In the first case the train lines would remain cancelled for the remainder of the day.

Besides the passenger service improvement, the reinsertion model decreases the level of stress for the rolling stock dispatchers. Solutions can be generated immediately to satisfy the demand of the train controllers in charge of the reinsertion decision. This has resulted in a more efficient planning process with resources left for other tasks.

Also the maintenance of the model has been eased to the satisfaction of the analyst updating it. The MIP model is easy to update according to a new periodic timetable. This is done simply by changing the set of constants presently used in the model and generating a new set of solutions.

7 Further Developments

Presently the reinsertion model is used only for scenarios where a cancelled train line needs to be inserted into a running operation, in which running trains can transport drivers to rolling stock depots. Future developments on the model could be to enable complete startups where trains can be inserted as the first on their route.

The present model works with a distribution of trains reinserted in each direction on intermediate depots of half reinserted in one direction and the other half reinserted in the other direction. Further developments on the model involves changing the constraints (6) and (7) to enable solutions where the number of trains reinserted in each direction on each intermediate depot are not bounded to be the half of the total number of trains to be inserted.

The number of trains to be reinserted on each depot is input to the model. Occasionally the number of trains available for operation on the depots is larger than the number of trains that has been taken out. It seems natural to change the model in order to account for this fact by deciding the optimal number of trains to be inserted from each depot, ensuring that the total number of trains reinserted is the number of trains needed to cover the line.

At some of the routes of the S-tog network more than two lines cover a route simultaneously. A relevant recovery scenario is that more than one line is cancelled along the route. It would be relevant to adjust the reinsertion model so that it can coordinate and give the results for the reinsertion of more than one line at a time. In the model this would mainly mean modification of input.

The quality of solutions generated by the reinsertion model strongly depends on the distribution of trains on depots. At the time of disruption, take out is carried out with no regards to a later reinsertion. There is no time for rearranging trains at depots so that the best possible reinsertion is possible at a later time. There will though be the possibility of making small changes in the take out plan. For example, it might be possible to drive forward to second closest depot instead of taking it out of operation at the closest depot. This can also be considered by the model.

8 Conclusion

We have presented a MIP model for generating optimal reinsertion plans of an entire, cancelled train line. The solutions generated by the reinsertion model are fully applicable in operation i.e. it is non-complex to derive a practical solution from a solution found by the model.

The reinsertion model is employed in operation today. The solutions generated with the reinsertion model always generates optimal solutions with respect to the latest inserted train. This was often not achieved when the reinsertion was calculated by hand. Frequently, the train line remained cancelled for the remainder of the day.

The MIP model is easy to update according to a new periodic timetable. This has decreased the possibility of the rolling stock dispatchers having to wait for an updated version.

Earlier the difficulties in calculating a reinsertion plan prevented different factors from being taken into consideration cf. Section 6. The significantly decreased solution time of the reinsertion problem (when comparing solutions made in hand and solutions generated with the reinsertion model) gives the possibility of adjusting the reinsertion carried out in operation and adjusting the reinsertion model accordingly.

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