



Rolling Stock Planning at DSB S-tog - Processes, Cost Structures and Requirements Technical Report

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Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Thorlacius, P. (2015). *Rolling Stock Planning at DSB S-tog - Processes, Cost Structures and Requirements: Technical Report*. DTU Management Engineering.

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Rolling Stock Planning at DSB S-tog

Processes, Cost Structures and Requirements

Technical Report

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November 3, 2015

Abstract

A central issue for operators of suburban passenger train transport systems is providing sufficient number of seats for the passengers while at the same time minimising operating costs. The process of providing this is called rolling stock planning. This technical report documents the terminology, the processes, the cost structures and the requirements for rolling stock planning at DSB S-tog, the suburban passenger train operator of the City of Copenhagen. The focus of the technical report is directed at practical train operator oriented issues. The technical report is thought to serve as a basis for investigating better methods to perform the rolling stock planning (to be the topic of later papers). This technical report is produced as a part of the current industrial Ph. D. project to improve the rolling stock planning process of DSB S-tog.

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1 Introduction

This technical report deals with the planning of rolling stock for DSB S-tog, the suburban passenger train operator of the City of Copenhagen.

1.1 The Purpose of Rolling Stock Planning

The overall purpose of *rolling stock planning* is to supply train seats in time and space to fulfil the passenger demand while minimising operating costs. This is conducted by assigning rolling stock *train units* to *train services*. As such, a train service is served by one or more train units and runs between an *origin station* and a *terminal station* calling at zero or more intermediate stations on the way at points in time as stipulated in the *timetable*. When passenger demand is high, train units providing a high seating capacity should be assigned to the individual train service. When demand is low, a minimum of train units may be assigned to the individual train service.

1.2 How This technical report is Organised

This technical report sets out in chapter 2 by defining the terminology used. Chapter 2 thus provides the answer to the question: *What do we call the different aspects of rolling stock planning?*

Next, chapter 3 describes the rolling stock planning process of DSB S-tog and its subprocesses. Chapter 3 is thus the answer to the question: *How is rolling stock planning performed at DSB S-tog?*

Chapter 4 describes the cost structures related to operating the rolling stock, answering the question: *What factors of the operation induce what cost?*

A rolling stock plan must adhere to a number of practical, railway oriented requirements. These requirements are described in detail in chapter 5. An overview of the requirements may be found in table 3 on page 14. This table also shows which requirements are handled in which of the subprocesses of the rolling stock planning process. As such, chapter 5 answers the question: *What requirements do we need to take into account when performing rolling stock planning?*

Finally, chapter 6 presents an outlook to future research.

2 Terminology

This chapter contains brief definitions of the most important terms used in this technical report. References to more detailed descriptions of the terms and their implications are given where applicable. Terms in *italics* refer to other definitions in the list.

- A **station** is a point in space where a *train service* may stop to allow passengers to get on or off.
- A **train service** is the concept of transport using trains on the main railway tracks, provided as a service to passengers and/or to perform *positioning* of *train units*. A *train service* runs between an *origin station* and a *terminal station* stopping at or *skipping* zero or more *intermediate stations* on the way at points in time as scheduled in the *timetable*.

- A **revenue train service** is a *train service* provided for the transport of passengers for revenue.
- A **non-revenue train service** is a *train service* that is running without passengers in order to *position* the *train units*.
- **Skipping** is when a *train service* passes a *station* without stopping. *Skipping* occurs as scheduled in the *timetable* for express *train services*, in disruption management for delayed *train services* to catch up, and for *non-revenue train services* that carry no passengers.
- **Positioning** is the process of moving *train units* in one or more *train services* in order to meet later demand for seats or technical maintenance at other points in space.
- **Revenue positioning** is the *positioning* of *train units* by providing more *train units* in a *revenue train service* than is in demand by passengers, thus offering excess seating capacity.
- **Non-revenue positioning** is *positioning* in *non-revenue train services* with no passengers. This is also known as dead-heading.
- A **timetable** is a complete list of *revenue* and *non-revenue train services* for a given period of time. Only the *revenue train services* are published to the general public. For details, see section 5.1.2.
- An **origin station** is a *station* from which a *train service* starts.
- A **terminal station** is a *station* at which a *train service* ends.
- An **intermediate station** is a *station* during the run of a *train service* at which the *train service* may either be stopping or *skipping*.
- The **train drivers** constitute the staff group performing *train services*. *Train drivers* also perform the part of *train shunting* that is to and from *side tracks*.
- A **depot** is the entire infrastructure at a *station* used for *train shunting* and parking of *train units* at *depot tracks*. All *depots* have facilities for cleaning and some have facilities for maintenance.
- A **maintenance depot** is a *depot* with maintenance facilities.
- A **depot station** is a *station* which has a *depot*.
- A **depot track** is a track at a *depot* where *train units* may be parked when not running as a *train service*.
- A **split depot** is a *depot* at a *station* at which some of the *depot tracks* are only reachable from some of the *platform tracks* and vice versa. Hillerød station has a split depot, as seen on Figure 2 on page 15.
- A **terminal depot** is a *depot* located at a *terminal station*.
- A **same direction depot** is a *terminal depot* located so that *train services* arriving to its *depot station* may reach the *same direction depot* by continuing through the *depot station* in the same direction of movement. *Train shuntings* arriving from a *same direction depot* may also continue through its *depot station* in the same direction of movement to become *train services* departing from that *depot station*. Høje Tåstrup station has a *same direction depot*, as seen on Figure 2 on page 15. Note that the tracks below the station on Figure 2 belong to the maintenance workshop.
- An **opposite direction depot** is a *terminal depot* located so that *train services* arriving to its *depot station* may only reach the *opposite direction depot* by changing direction of movement at the *depot station*. *Train shuntings* arriving from an *opposite direction depot* must also change their direction of movement at the *depot station* to become *train services* departing from that *depot station*. Køge station has a *opposite direction depot*, as seen on Figure 2 on page 15.

- A **intermediate depot** is a *depot* located at an *intermediate station*. Train units entering an *intermediate depot* may continue in the same direction or must change direction depending on the direction in which they are arriving at the *intermediate depot*. København H station has an *intermediate depot*, as seen on Figure 2 on page 15.
- A **platform track** is a track at a *station* where a *train service* may stop and allow passengers to get on or off. A *platform track* may also be temporary used for the parking of *train units*.
- A **side track** is a track that can only be used for parking in the day time. There is no internal *train shunting* between side tracks.
- A **side track station** is a station which has *side tracks*. As opposed to a *depot station*, there are no facilities for cleaning or maintenance.
- A **train shunting** is the operation of coupling and decoupling *train units* at *depot stations* or *side track stations* as well moving the *train units* to and from *platform tracks*, *depot tracks* and *side tracks*.
- The **depot drivers** constitute the staff group performing those *train shuntings* that are in and out of a *depot*.
- A **train line** is an aggregation of similar *train services* according to the time of day they are running, the stations they are visiting etc.
- A **train service sequence** is a consecutive sequence of *train services*, on the same (or related) *train line*, for which it is a natural choice that the *train units* be reused from one *train service* to the next. The train service sequences of a *time table* may be determined from the layout of tracks, the minimum and maximum turnaround times between two consecutive *train services* at the *origin* and *terminal stations* and by the *braiding* policy. The concept of *train service sequences* is used to ease the manual rolling stock planning process. The first and last *train service* in a *train service sequence* may not require a *depot driver* to *shunt* the corresponding *train units* out from or into the depot, since the *train driver* for the *train service* has time to perform this operation as his first or last task in his duty.
- **Braiding** is when there are *train services* from different *train lines* in the same *train service sequence*. *Braiding* may yield better utilisation of the *train units* at the cost of a lower robustness since disruptions may then propagate between *train lines*. Under certain conditions *braiding* may produce *train service sequences* that represent one direction of one *train line* and the opposite of another, a highly undesirable feature from a robustness point of view. Forced *braiding* may also be used to raise the robustness by forcing higher turnaround times.
- **Depot internal shunting** is the the process of *train shunting* between depot tracks at the same *depot station*. A *platform track* may be involved in the process, but *depot internal shunting* starts at one *depot track* and finishes at another.
- A **train service segment** is the individual part a *train service* performs between *depot stations* or *side track stations* for that particular *train service*. Since there are no *depot stations* or *side track stations* en route on a *train service segment*, the *train composition* of a *train service* will remain constant.
- A **train shunting segment** is the individual part of a *train shunting* between *platform tracks*, *depot tracks* or *side tracks* for a particular *train shunting*. Analogous to *train service segments*, the *composition* remains constant in a *train shunting segment*.
- A **train unit** is the actual, physical, individual, inseparable railway vehicle. For details, see section 5.1.3.
- The **train unit type** is the technical type of a *train unit*. For details see section

5.1.3.

- A **train unit trajectory** is the path a *train unit* moves through consecutive *train service segments* and *train shunting segments* to fulfil its tasks over a period of time.
- A **train composition** is the ordered sequence of coupled, individual *train units* assigned to an individual *train service segment* or *train shunting segment*.
- A **train composition type** is the anonymous, non-ordered composition of a *train service segment* or *train shunting segment* specifying only *train unit types*. For details, see section 5.1.3.
- A **total composition exchange** is when all *train units* in two consecutive *train service segments* in a *train service sequence* are exchanged.
- A **partial composition exchange** is when only some of the *train units* in two consecutive *train service segments* in a *train service sequence* are exchanged.
- A **rolling stock plan** is the assignment of all available *train units* to *train unit trajectories* that combined satisfy the operational requirements. The set of *train unit trajectories* implicitly determines the *train composition* of each *train service segment* and *train shunting segment*. This implies how much seating capacity is offered in the individual *train service segments* and when and where *train units* are parked at the depots.

3 The Rolling Stock Planning Process

At DSB S-tog, the process of rolling stock planning is currently divided into two subprocesses. The first subprocess is the long term *circulation planning* and the second subprocess is the short term *train unit dispatching*. Aspects of these subprocesses are described in this chapter. Figure 1 shows an overview of the current rolling stock planning process at DSB S-tog and its subprocesses. Table 1 shows an overview of the different characteristics for the specific subprocesses *circulation planning* and *train unit dispatching with disruptions*.

(Note that at DSB S-tog, the routing of train services on the main line and through stations is not considered a part of the rolling stock planning process, but rather a part of the timetabling process. In the rolling stock planning process one can thus assume, that there is sufficient capacity on the tracks and in the stations to operate the given timetable.)

3.1 Aspects of Circulation Planning

The long term part of the current rolling stock planning process at DSB S-tog is called circulation planning. According to the current protocol, the circulation planning process must be started at least three months before and completed at least three weeks before the plan is to be commenced (that is, put into motion).

For this reason, at the time the circulation planning is conducted, it is not known which physical train units are available when the plan is to be commenced. Some train units may be in unscheduled maintenance, see section 5.2.2 and it is not known where the physical train units are situated at the time the plan is to be commenced, since changes to the previous plan may have occurred. For this reason the circulation planning is performed for *virtual train units*, that is, anonymous train units which have no individual characteristics apart from those involved in the plan.

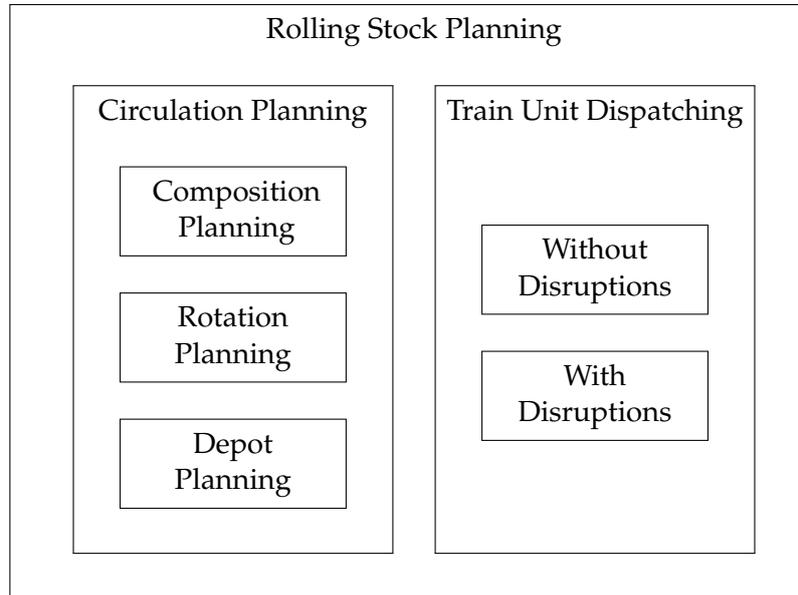


Figure 1: The rolling stock planning process at DSB S-tog and its subprocesses.

Table 1: Overview of the different characteristics for the processes *circulation planning* and *train unit dispatching with disruptions*.

Subject	Characteristics of the process <i>circulation planning</i>	Characteristics of the process <i>train unit dispatching w/disruptions</i>
Planning scope	The everyday operation	For occasionally occurring disruptions
Planning horizon	Long term	Short term (real time)
Time for processing	Long	Very short
Goal	Stable operation	To recover to stable operation
Instruments used	A limited number (to ensure simplicity and robustness)	Every possible one (to ensure operation is resumed quickly)
Requirements	Strict (planned violation not tolerated)	Not so strict (one-time violations tolerated)
Cost of plan	Important (cost is incurred every day)	Not so important (cost is incurred only once)

The term circulation planning is thus analogous to the term *crew pairing* in the airline industry, except in this case the pairing is performed for virtual train units, not virtual crew members [5].

At DSB S-tog the circulation planning is currently performed as three separate subprocesses that are executed one after the other as *composition planning*, *rotation planning* and *depot planning*. These three subprocesses are described in the following sections, and may also be seen on figure 1.

3.1.1 Composition Planning

The subprocess of deciding how many virtual train units to assign to a train service in order to meet passenger demand is called *composition planning*. The main requirements to this process are the infrastructure, the rolling stock, the timetable and the passenger demand (see sections 5.1.1 to 5.1.4). The output of the process is a composition plan defining the amount of virtual train units to assign to each train service, making sure that the overall depot track length of each of the depots is not exceeded by parked train units at any time, that each virtual train unit can only be part of one train service at a time, and that train unit balance is kept.

3.1.2 Rotation Planning

The next subprocess is called *rotation planning* and deals with deciding which virtual train unit is to move from a position in a train composition serving one train service segment to a position in a next train composition serving the next train service segment (possibly with a stop-over at a depot). This subprocess also takes into account when and where the virtual train units should undergo scheduled maintenance, which, apart from the composition plan, is the main requirement for this subprocess. The scheduled maintenance requirements are described in section 5.2.1 on page 24.

Typically, when there is not much change in passenger demand, a train unit in service on a particular *line* (see explanation on figure 3, page 17) stays on that line when changing direction at the terminal station. Thus a train unit used in a train on a line in one direction typically *rotates* to become part of a train service in the opposite direction on the same line when it reaches the terminal station.

As mentioned in chapter 2, a series of train services for which it is a natural choice that the rolling stock train units be rotating from one train service to the next is called a *train sequence*. Normally, train sequences are for the same line. Under certain conditions however, it may be more desirable to intertwine two lines to use the same rolling stock train units so that the train units change the line at one common terminal station. Such *braiding* train sequences may provide a better utilisation of the rolling stock at the cost of the *robustness* of the plan, that is, the ability of the plan to contain outside influences with few negative consequences. The robustness of the plan is reduced since a delay on one line will propagate to the other line with which the delayed line shares its rolling stock train units. Furthermore, the robustness is reduced because it may be much harder to recover manually from a disruption since the movement pattern of the individual train units is more complicated.

3.1.3 Depot Planning

The subprocess of deciding how a virtual train unit is to be parked in a depot (when not needed to perform train services) and how it is to be retrieved again (when it is needed once more) is called *depot planning*. Apart from the rotation plan produced in the previous step, the main requirements for this subprocess are the infrastructure and the personnel on duty, see sections 5.1.1 and 5.1.5.

Some train operators do not consider depot planning a subprocess of circulation planning, but rather a separate process in itself [1]. This is presumed to be for the reason that those operators have sufficient capacity in the depots to perform the depot planning process completely independent of the rest of the rolling stock planning processes. As mentioned, this is not the case for DSB S-tog.

In literature, the term *shunting* is used for the process of coupling and decoupling of train units and parking them in the depot [3]. At DSB S-tog, the more general term *depot planning* is used including other processes like cleaning as well, not only shunting.

At DSB S-tog, the process of assigning depot drivers to the individual shunting tasks is also a part of the depot planning process. This subprocess is called *depot driver scheduling*.

3.2 Aspects of Train Unit Dispatching

At DSB S-tog, the process of commencing a circulation plan (that is, putting the plan into motion) is called *train unit dispatching*. The time horizon for this process ranges from short (two days) to real-time.

The overall purpose of the process is to assign actual, physical train units to the virtual train units in the circulation plan. As such, train unit dispatching is analogous to the term *crew rostering* in the airline industry, except in this case the rostering is performed for train units, not crew [5].

The train unit dispatching process has two subprocesses each of which are performed under different conditions. The process of dispatching train units is as such different depending on whether disruptions are occurring or not, and different requirements must be taken into account in the two subprocesses. This is shown in table 3 on page 14 and the subprocesses themselves are explained in the following two sections.

3.2.1 Train Unit Dispatching in a Situation without Disruptions

When no disruptions occur, the object of the train unit dispatching process is to assign a physical train unit to each virtual train unit in the circulation plan. While doing so, it must be taken into account that the virtual train unit is planned to go into maintenance before the maintenance service distance limit of the physical train unit has been reached. Furthermore, all of the requirements which were not taken into consideration in the circulation planning process need to be considered. This is shown in table 3 on page 14.

The general idea (and purpose) is that the requirements already handled in the circulation planning process need not be considered in the train unit dispatching process when no disruptions are occurring.

3.2.2 Train Unit Dispatching in a Situation with Disruptions

In reality disruptions may occur at any time influencing how the plan (or parts of it) may be realised. A *robust* circulation plan is able to accommodate these outside influences with few changes to the original plan (timetable including) and a minimum of negative consequences for the passengers and the train operator.

At DSB S-tog, when a disruption occurs, the *train controller* of the infrastructure owner (BaneDanmark) is in charge of the overall recovery process, with the *train unit dispatchers* of DSB S-tog as co-operating partners.

In the case of disruptions, the train controller and train unit dispatchers may decide to disregard some of the requirements that needed consideration in the situation without disruptions. This is as to be able to handle a disruption before it gets out of hand. In the event of a disruption, it is of the utmost importance that sufficient action is taken sufficiently quickly so as to contain the disruption and to prevent it from propagating into the entire network. Furthermore the action taken needs to be so as to be able to return to normal service as quickly and with as few changes to plan as possible.

The instruments the train controller may use to conduct the recovery process may include:

1. Cancelling individual train services, partially or completely, and cancelling entire lines;
2. Making individual train services skip planned stops at stations to make up for lost time;
3. Delaying train services.

The characteristics of the disruption and the instruments applied to remedy it provide the conditions the train unit dispatchers will have to compensate for, since physical train units may not be where the circulation plan states the corresponding virtual train units should be.

In the event of a disruption directly caused by a sudden train unit breakdown (requiring that the train unit must undergo unscheduled maintenance), the train controller and train unit dispatchers may choose solution strategies depending on the characteristics of the breakdown of the train unit(s) in the train. These characteristics may include:

1. Can the train composition move by itself?
2. Can the train composition accelerate normally?
3. Can the train composition travel at normal speed?
4. Is the train composition or train unit allowed to carry passengers?

Solution strategies (multiple of which may be chosen) may include:

1. Off-load passengers at nearest station;
2. Get the train composition or train unit out of the way in order not to obstruct the movement of other train services. In extreme cases this may involve getting another train unit or locomotive to provide traction;
3. Get the the train composition or train unit to a side track or depot where it may either wait or be repaired by the mobile repair crew;
4. Get the train composition or train unit into one of the two maintenance workshops;

5. Assign the physical train unit to run as a virtual train unit on the line that passes the main maintenance workshop so as to let the workshop pick out the train unit for maintenance when maintenance may be conducted;
6. Pick another train unit from the reserves to replace the one that has been taken out of service. Reserves are at Hundige, København H and Høje Tåstrup stations.

In the recovery phase after a disruption, one goal of the train unit dispatchers is to reach the depot balance of the original circulation plan. By doing so, the dispatchers may ensure that the actual operations may return to being very close to or according to the original circulation plan since the number of rolling stock train units in the depots will be correct.

When reinstating train services on cancelled lines, certain rules must be adhered to. For example, if reinstating a cancelled train service, all subsequent train services on the given line must also be reinstated.

In the event of a disruption, the train unit dispatchers have at their disposal instruments that are not available to the planners in the planning phase. These instruments include the cancelling of train services, disregarding business rules regarding train unit order in the train composition, disregarding rules about number of train units in a train composition, disregarding rules as to how train units may be coupled, and others. These *dirty tricks* are allowed in the recovery phase to prevent worse things from happening.

After a disruption, the physical train units may not be parked according to the circulation plan at all. Which physical train units may run as which virtual train units (as defined in the circulation plan) is then highly dependent on how the physical train units are actually parked in the depot.

As may be concluded from the previous paragraphs, in the event of disruptions, the work of the train unit dispatchers always deals with compensating for the unexpected events that may occur. If a train unit breaks down, a compensation train unit must be provided from the reserves. If train services are cancelled in the event of a disruption and the depot balance of a depot is not according to plan, train units must be positioned to compensate for this.

4 Cost Structures for Rolling Stock Operation

4.1 Background and Terminology

The primary objective of moving train units around on the tracks of a railway is of course to provide seats for the transportation of passengers. As such, most of the train unit movements depend upon the given timetable. In order to be able to accommodate passenger demand at all times, train units must often be moved from one location to another before the actual demand occurs. This type of movement is called *positioning* and may be conducted as an individual train service without passengers as *non-revenue positioning* or as *revenue positioning* by running passenger carrying train services with more train units than the immediate demand for that particular train service. In the latter case, the train unit being positioned is used as a functional part of the train composition.

Table 2: Overview of the different different types of operating costs for a suburban train transport company in this case DSB S-tog. *Primary acceleration energy* is the energy needed to accelerate the train composition to cruising speed upon departure from its origin station. Analogously, *subsequent acceleration energy* is the acceleration energy needed at subsequent stations. *Speed sustainment energy* is the energy needed to sustain cruising speed. The costs for energy and maintenance for half-length type of train units are a bit more than half of that of the full-length type of train units.

Type of cost	Proportional to	Incurred by revenue positioning	Incurred by non-revenue positioning
Primary acceleration energy	# of train units of type	Yes	Yes
Subseq. acceleration energy	# of train units of type at station	Yes	No
Speed sustainment energy	# of train units of type service dist.	Yes	Yes
Maintenance	# of train units of type service dist.	Yes	Yes
Infrastructure	Revenue train service distance	No	No
Train driver duties	Engine drivers hired	No	Possible
Depot driver duties	Depot drivers hired	Possible	Possible

4.2 Operating Cost Types and Structure

As may be seen from table 2, seven different types of operating costs are relevant for DSB S-tog as a suburban passenger train operator. The different types of costs are proportional to different factors of the operation, and are, as such, incurred by revenue or non-revenue positioning as stated in the table and described in the following.

All train units in a train composition need primary acceleration energy to reach cruising speed upon departure from the origin station, regardless of whether the train units perform revenue or non-revenue positioning. However, since a non-revenue positioning train service is not stopping at intermediate stations, no subsequent acceleration energy is needed. The energy needed to sustain cruising speed is proportional to the distance each train unit moves, regardless of positioning type.

The maintenance costs are also proportional to the distance each train unit moves, and as such, regardless of positioning type.

The fee for using the railway infrastructure is only levied for revenue train services. As such, there is no extra infrastructure cost for non-revenue positioning. There is also no extra infrastructure cost for revenue positioning, because the fee has already been paid for the train service that is involved in the revenue positioning, since this train service runs with passengers according to the given timetable. In this sense, one could say that the infrastructure costs are solely determined by the given timetable.

Similarly, the train driver duty costs are strongly dependent on the given timetable since each train service must have a train driver. If a decision is made to perform a revenue positioning, this will not induce additional driver duties, since the train service already has a train driver. However, deciding to perform a non-revenue positioning may (under certain conditions) require that another train driver be hired to drive the train composition to be positioned (if the number of train drivers hired and on duty is not sufficient to perform this task).

The costs related to the depot drivers are proportional to the number of depot drivers hired. Under certain conditions there may not be enough depot drivers hired and on duty to perform the train movements that may be required to perform a positioning, regardless of positioning type. In this case, additional depot drivers must be hired, thus inducing a higher cost.

Note that the energy and maintenance costs for half-length type of train units are a bit higher than half of that of the full-length type of train units.

4.3 Costs not Considered

Of course a train unit that undergoes revenue positioning is being worn more and needs more interior cleaning than a train unit that undergoes non-revenue positioning, since it is carrying passengers. However, since there will also be fewer passengers in the other train units of the train composition, this effect is considered negligible.

The energy usage for train movements in the depot is also considered negligible.

5 Practical Requirements for Rolling Stock Planning

This chapter describes the practical, train operator oriented requirements for rolling stock planning. For an overview of the requirements, please refer to table 3.

Each requirement is either dependent or independent of the individual physical train unit. This distinction may prove important in the later modelling process since the number of possible combinations may be highly reduced when one is not required to take combinations of all the individual train units into account but only the train unit type.

Table 3 also shows in which subprocess in the current planning process the requirements are handled.

On a general note, it is general practice at DSB S-tog, that exemptions from the requirements described here may be made. Such exemptions are made in order to make a manually produced rolling stock plan work in the “real world”, i. e. with the resources given. This of course makes it harder to model the rolling stock planning process as it is currently performed, since it is not generally known which requirements may be exempted by which conditions. It also makes it harder to compare plans created manually with plans created automatically.

5.1 Requirements Independent of the Individual, Physical Train Unit

This section describes the requirements to the rolling stock planning process that are independent to (that is, not related to) the individual physical train unit. For example, the requirements related to the infrastructure are independent of the individual physical train unit because it does not matter which individual physical train unit of a given type occupies a track. Any other individual physical train unit of that type may just as well occupy that track.

5.1.1 Infrastructure

One of the main requirements for rolling stock planning is of course (as with almost all other aspects of railway operation planning) given by the railway infrastructure.

Table 3: Overview of the requirements for rolling stock planning at DSB S-tog. In the table the column *Indep.* means independent of the actual, physical train unit, the column *Circ.* means handled in the rolling stock circulation planning process, *No Disr.* means handled in the train unit dispatching process when there are no disruptions, and *Disr.* means handled in the train unit dispatching process when disruptions have occurred and a recovery is in progress. Statements in parenthesis indicate likely future decisions.

Section	Requirement	Indep.	Circ.	No Disr.	Disr.
5.1.1	Infrastructure	Yes	Yes	No	Yes
5.1.2	Timetable	Yes	Yes	No	Yes
5.1.3	Rolling Stock	Yes	Yes	No	Yes
5.1.4	Passenger Demand	Yes	Yes	No	Yes
5.1.5	Personnel on Duty	Yes	Yes	No	Yes
5.2.1	Scheduled Maintenance	No	Yes	Yes	Yes
5.2.2	Unscheduled Maintenance	No	No	Yes	Yes
5.2.3	Friction Sand	No	No	Yes	Yes
5.2.4	Exterior Cleaning	No	No	Yes	No
5.2.5	Exterior Graffiti Removal	No	No	Yes	No
5.2.6	Interior Cleaning	No	No	Yes	No
5.2.7	Winter Preparedness	No	No	Yes	No
5.2.8	Exposure of Commercials	No	No	Yes	No
5.2.9	Surveillance Video Requests	No	No	Yes	No
5.2.10	Surface Foil Application	No	No	Yes	No
5.2.11	Passenger Counting Equipment	No	No	Yes	No
5.2.12	Train Control System Equipment	(No)	(Yes)	(No)	Yes

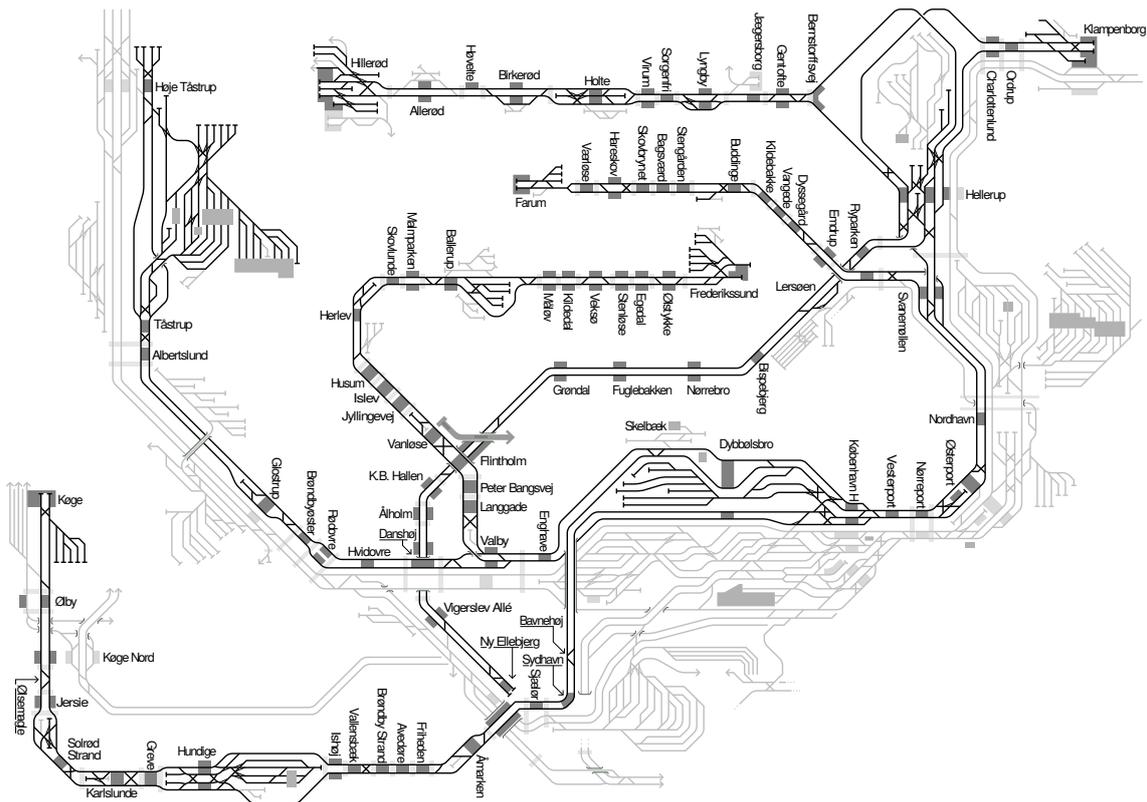


Figure 2: The railway infrastructure available to DSB S-tog. Tracks which may be used by DSB S-tog are printed in black. Other tracks used by the long distance train services and the metro (only connecting tracks are printed) are printed in grey [4].

The railway infrastructure consists of tracks, points, stations, platforms, depots (where rolling stock may be parked when not in use) and maintenance workshops (where maintenance on the rolling stock may be carried out).

The infrastructure available to DSB S-tog is shown in figure 2. At present, DSB S-tog is the sole operator on these tracks. As may be seen (even more clearly from figure 3 on page 18), the infrastructure consists of 6 *fingers*, with a shared *central segment* between stations Svanemøllen and København H and a radial line, the so-called *circular line*.

The track part of the infrastructure requirements relates to physical track capacities (how many train units may use a particular part of the infrastructure) and track topology (how the infrastructure parts are interconnected). The physical track capacities can at no time be exceeded. Furthermore overtaking is of course not possible.

Recall from section 3 that at DSB S-tog, the routing of train services on the main line and through stations is a part of the timetabling process. As such, the infrastructure requirements for train services have already been met with a given timetable and need not be considered in the rolling stock planning process. However, other infrastructure requirements do need to be considered.

For the case of DSB S-tog, the track infrastructure at the central segment is a highly limiting constraint as to which train operations may be performed since most train services pass through here and the track capacity in this segment is thus highly utilised.

Furthermore, the depot infrastructure is also a highly limiting constraint on the possible train operations (in relation to rolling stock planning). This is because the track capacity of the individual depots is very limited, and also because the track layout of some depots is strongly limiting the movements that may be conducted with the

rolling stock.

There are two workshops where maintenance may be carried out, the main workshop in Høje Tåstrup and a subsidiary workshop in Hundige. The latter workshop is staffed on demand by a mobile repair crew and is only used in special cases. All scheduled maintenance tasks are carried out in the main workshop in Høje Tåstrup. Some maintenance tasks may be performed in both workshops, some only in the main one in Høje Tåstrup.

The location of the depot at København H in relation to the lines defined in the timetable (see section 5.1.2) means that rolling stock parked here may be put into service on any line (including the circular line, since both Klampenborg and København H depots serve as depots for this line).

Other infrastructure related requirements are the *track usage rules*, business rules stating which track to use for a specific line and direction.

Train movements, that is, the motion, coupling and decoupling of train units are also governed by the infrastructure in four ways:

1. The train control system enforces rules for the train movements. The current train control system is based on external and internal visual signals to which the train driver has to act, as well as automatic emergency braking if he or she fails to do so. In small parts of the network manual train control is performed using an electro-mechanical train control system. The other large part of the network has an automatic system.

Presently, the rules of the existing train control system allows coupling of train units depending on whether the train service is a revenue or non-revenue train service and whether the last train in the coupling process is arriving from the depot or from the main line. Simplified, it is allowed to have any train unit parked at a platform track and then coupling this train with a train arriving from the depot or a non-revenue train arriving from the main line. It is disallowed to couple a train composition running as a revenue train service arriving from the main line with any train unit parked at the platform track.

A new communication based train control system (CBTC) without external visual signals will be rolled out from 2014 to 2018. The new system will prove less restrictive as to the allowed train movements.

2. In the process of decoupling train units from each other in a train composition, a business rule states that it is disallowed to decouple two parts of a train composition and letting the part that is going to continue as a revenue train service depart before the other part has been driven off into the depot. This is because passengers may get confused when parts of the train composition are in service, and other parts not. Furthermore, a movement like the one described must be conducted after the revenue train service has departed. A depot driver may then not have time to perform another depot movement for the next train service if this movement is to occur before the next revenue train service departs.
3. Another business rule states that no coupling or decoupling may take place on a train composition en route from its origin station to its terminal station. This would run the risk of being too time consuming and thus delay other train services. When changes in the number of train units in a train composition must be performed en route, a new set of train units is collectively driven in from the

depot to one of the platform tracks. This new set of train units then replaces the old set arriving at the other platform track, and is afterwards collectively driven into the depot. This type of movement is called a *total composition exchange* as opposed to a *partial composition exchange*, in which parts of the train composition are retained.

4. A business rule states that there can be only one train movement to each coupling or decoupling. As such, it is disallowed to split a train composition into two before driving each of the two parts off into the depot. The opposite movement is also disallowed. This business rule is in place to enforce simplicity and robustness. If more movements for each coupling or decoupling would be allowed, the train units would occupy the platform tracks for much longer periods of time, with a higher risk of delaying otherwise uninvolved train services.

5.1.2 Timetable

Another main requirement for rolling stock planning is the timetable. The timetable states which train services must be run and to which rolling stock must therefore be assigned. The timetable implicitly also states which lines will be running between stations and where and when train services must be stopping at stations, see figure 3.

For the case of DSB S-tog, the timetable is highly dependent on the existing contract with the Ministry of Transport [9]. This contract states a minimum number of train services to be run on given lines at given time intervals and at which minimum frequency the different stations must be served. As such, DSB S-tog may only to a very limited degree vary the supplied seats in time and space by varying the frequency of operation. Thus, the seat supply must be varied using different train compositions. Also, DSB S-tog is allowed to redistribute a certain number of train service kilometres within the contract.

The current timetable is a cyclic timetable with the following characteristics on a normal weekday in the day time: The red H line runs every 20 minutes. So does the light green Bx line, but in the morning rush hour only. The yellow F line runs every 5 minutes. All other lines run every 10 minutes. When the line letter is printed inside the line (e. g. the blue A that is printed between stations Hundige and Greve) the frequency of operation is lower between the letter and the nearest terminal station or this part of the line is only served at certain periods of the day.

In the evening and in the weekend, the frequency of operation is reduced and a different line concept is used. In the weekend a four-line concept is used. In the night time after Friday and Saturday a completely different timetable with four lines is operated with a frequency of 30 minutes.

Timetables come in various sorts: The *standard timetable* covers the base, standard case when no extraordinary events are planned anywhere on the network. Subordinate *extraordinary timetables* cover special cases, for example when infrastructure works on a particular part of the network are performed. Typically an extraordinary timetable is very much like the standard timetable, in fact it is often considered an advantage that there be as little difference between the standard timetable and an extraordinary one as possible. When the differences are small, planning is easier, and most importantly, the job of informing the public and employees of the changes is strongly facilitated.

When larger infrastructure works are conducted, however, it may not be possible to achieve this similarity. In the case where the infrastructure works are comprehensive in



Figure 3: The graphical representation of the DSB S-tog timetable valid from December 2012 to December 2013 for weekdays. Each line is represented by a different colour. There is a different line concept on weekends and at night.

Table 4: Number of days when the standard timetable is in effect on the entire network of DSB S-tog.

Year	2008	2009	2010	2011	2012
Number of days in effect	72	177	27	53	80

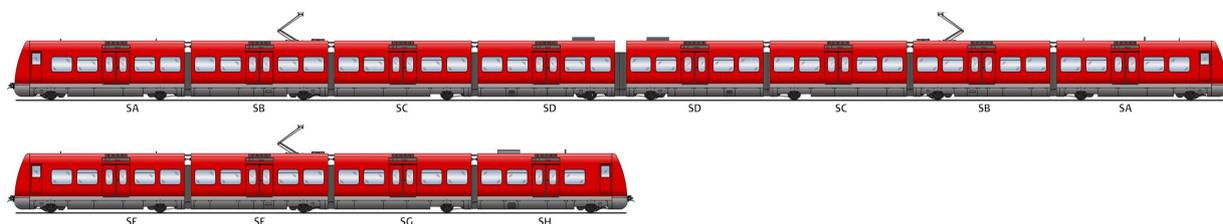


Figure 4: The DSB S-tog train unit types types 1 (top) and $\frac{1}{2}$ (bottom).

time and space, it may be of advantage to have a *standard extraordinary timetable* for the general case of the infrastructure works and subordinate *extra-extraordinary timetables* relating to the standard extraordinary timetable.

Note that in some years, the standard timetable may only be in effect on a very limited number of days, see table 4. All the other days, extraordinary timetables are in effect. However, an extraordinary timetable usually only changes a small portion of the entire operation, e. g. changes in relation to infrastructure work on one of the two tracks on one of the fingers. The lines running on the other fingers are then running according to the standard timetable (if at all possible).

In 2012, the timetable gave rise to a total service distance of 16,9 million train service km.

5.1.3 Rolling Stock

DSB S-tog has two types of rolling stock train units with the technical designation *Litra SE* and *Litra SA*. In this technical report the train unit types are designated 1 and $\frac{1}{2}$ for Litra SA and Litra SE respectively, indicating that the Litra SE are approx. half as long as the Litra SA. Other characteristics of the train unit types are given in table 5 and the visual appearance is shown in figure 4.

Apart from the differences given in table 5, an important difference between the two types of rolling stock is the amount and distribution of flexible space for bicycles, baby carriages and wheelchairs. Type 1 train units have flexible space at both ends of the train unit, that is, in the first and in the eighth carriage. DSB S-tog is in the process of rebuilding all type 1 train units to also have a flexible space in the middle of the train unit, that is in carriage 4 and 5. This will double flexible space provided. Type $\frac{1}{2}$ train units only have one flexible space, and this is situated in the most northern carriage.

Due to three different constraints (described below), train units in revenue service may only be coupled together to form five different composition types as shown in table 6.

1. **Platform length:** When carrying passengers, it must be possible to stop the train composition so that all doors are at the platform. The stations fall in two categories, those with a platform length equivalent to one type 1 train unit (on the

Table 5: Rolling stock train unit types of DSB S-tog. All train units are *Electrical Multiple Units (EMU)*. *Nominal number of seats* is the actual number of physical seats in the train unit. *Perceived number of seats* is the number of passengers that may be transported in the train unit perceived by the passengers as being full with regard to seats.

Train unit type	Technical designation	Nominal # of seats	Perceived # of seats	Carriages	Length [m]	# of train units
$\frac{1}{2}$	Litra SE	150	125	4	42.58	31
1	Litra SA	336	300	8	83.78	104

circular line, Line F), and those with a length equivalent to two type 1 train units (on the rest of the network). Note that because of the fact that the type $\frac{1}{2}$ train units are only slightly longer than half of the type 1 train units, it is possible to have a train composition consisting of two type $\frac{1}{2}$ train units on stations that can accommodate a type 1 train unit in platform length, however it **is not** possible to have a train composition with one type 1 train unit and two type $\frac{1}{2}$ train units on stations that can accommodate two type 1 train units (even though this train composition type is only 1.18 m longer).

2. **Number of train units in the train composition:** In the planning scope, train compositions may not consist of more than two units at a time. In practice, e. g. in the event of a disruption, more units may be coupled together, however this may require some of the units to run without traction thus giving the train composition reduced acceleration capabilities. Furthermore, in the event of a brake failure, manual intervention by the train driver will be required, possibly at the other end of the train composition. As such, coupling more than two units together is not robust since it is prone to delays possibly occurring at critical sections of the network.
3. **Amount of flexible space and its distribution:** Type $\frac{1}{2}$ train units only have flexible space in the most northern of its four carriages. In order to achieve that there always be flexible space in the first and last carriage of all train compositions, a business rule states that a type $\frac{1}{2}$ train unit may only be coupled to the north of a type 1 train unit. If it were to be coupled to the south, the train composition would have no flexible space in the most southern carriage. The business rule is in place to prevent delays arising when passengers are not able to find a carriage with flexible space to enter. For train compositions only consisting of train type $\frac{1}{2}$ train units, which may be used when demand is low, this rule is exempted, since corresponding passenger-induced risk of delay is also low. Train compositions of type $\frac{1}{2}$ are usually only allowed on the F line. Currently, another business rule only allows compositions $\frac{1}{2}$ and $\frac{2}{2}$ on the F line, since these compositions would often not provide enough flexible space on the other parts of the network even though passenger demand is low. Exempts from this business rule are made in special cases. The need for this business rule is currently being evaluated.

In tables 5 and 6, note the distinction between *nominal number of seats*, which is the actual number of physical seats in the train unit and *perceived number of seats*, which is the number of passengers that may be transported in the train unit perceived by the passengers as being full with regard to seats. If the perceived number of seats

Table 6: Possible train unit compositions for revenue train services at DSB S-tog. *Perceived number of seats* is the number of passengers that may be transported in the composition perceived by the passengers as being full with regard to seats. Additionally, compositions of type $\frac{3}{2}$, 3 and others exist but these are only allowed under special conditions.

Composition type	Train unit types in composition	Perceived # of seats	Total Length [m]	Allowed on lines
$\frac{1}{2}$	$\frac{1}{2}$	125	42.58	F only
$\frac{2}{2}$	$\frac{1}{2} + \frac{1}{2}$	250	85.16	F only
1	1	300	83.78	All but F
$1\frac{1}{2}$	$1 + \frac{1}{2}$	425	126.36	All but F
2	1 + 1	600	167.56	All but F

is exceeded by the number of passengers, DSB S-tog experiences a sharp rise in the amount of customer complaints for seat shortage. That the passengers are not using all available, physical seats has to do with the physical layout of the interior of the train units combined with the desire by passengers to sit in a particular end of the train composition.

Note that since a type $\frac{2}{2}$ composition (as shown in table 6) is more expensive than a type 1 composition (see section 4.2), a type $\frac{2}{2}$ composition is only used when revenue positioning is needed, when there is a shortage of type 1 train units, or when operation conditions do not make it possible to use type 1 compositions. In practise, type $\frac{2}{2}$ compositions are almost only used on the circular line, Line F, and only in the rush hours. At other times, type $\frac{1}{2}$ composition is used for Line F. Using type $\frac{2}{2}$ compositions at Line F instead of type 1 compositions is advantageous since type $\frac{1}{2}$ and $\frac{2}{2}$ compositions use the same type of train units, making it easy to change composition under the conditions given at Hellerup station. A type 1 train unit as running as a type 1 composition on Line F would have to perform non-revenue positioning all the way to and from Klampenborg or København H depots for the required total composition exchange (see section 5.1.1) and would demand a train driver en route to the depot station and depot driver resources at the depot. Type $\frac{1}{2}$ train units, on the other hand, can easily be parked by the train drivers at the side tracks at Hellerup station, neither demanding non-revenue positioning, extra train driver duties nor depot driver resources.

5.1.4 Passenger Demand

Another one of the main requirements for rolling stock planning is of course the expected passenger volume, that is, how much demand is expected for seats in the train services given by the timetable.

The recent trend of the overall passenger demand is shown in table 7.

DSB S-tog is in the very fortunate position of having very good data on passenger demand, since all train units weigh passengers at departure from every station. The weighing mechanism is part of the secondary suspension system of the train unit. In order to keep the floor of the train unit in the same level as the platform regardless of

Table 7: Passenger demand development at DSB S-tog.

Year	2007	2008	2009	2010	2011	2012
Transported passengers [Million]	89	91	95	97	104	108

how many passengers are on board, a valve triggered by the distance between the axle axis and the carriage frame regulates the inflation of a bellows. Measuring the pressure of the bellows may then be used to calculate the number of passengers in the train unit with a typical accuracy of three to five persons in a type 1 train unit.

The measurements are transmitted from the train computer to a central database. On an average weekday approx. 28,000 measurements are recorded, one for each train service leaving a station.

DSB S-tog has developed an advanced statistical model to handle the passenger demand data. In this passenger demand model, the data is categorised according to day type (at present Monday to Thursday as one day type, and Fridays, Saturdays and Sundays as individual day types). The model itself uses exponential smoothing as a statistical method to handle the daily fluctuations on the passenger demand data while preserving information about possible trends. The exponential smoothing is applied to both the mean value as well as to the standard deviation parameters in the process.

Furthermore the passenger demand model applies different methods to ensure the quality of the input data by correcting its values under given criteria. It is also possible to exclude given dates (e. g. with disruptions) from the processing as well as given stations. At DSB S-tog, the latter option is used in general, so that the central segment (see definition in section 5.1.1) is disregarded when dimensioning the number of seats to make available in each train service. The justification behind this procedure is that in the central segment, the frequency of operation is very high and travelling times short, therefore it is acceptable that there be standing passengers. Otherwise excessive capacity would be provided at the fingers (see definition in section 5.1.1).

The passenger demand model may deliver figures to be used as the dimensioning passenger demand dependent of one of the following two different concepts:

1. **Comfort Level:** The fraction of passengers that will have a seat in each individual train service over a number of days. If the comfort level is set to 0.95, the model calculates the dimensioning passenger demand so that 95% of all passengers in this train service (over a number of days) will have a seat. This concept is centred around the travel experience of the individual passenger, thus the name.
2. **Service Level:** The fraction of the occurrences of a train service over a number of days in which all passengers will have a seat. If the service level is set to 0.95, the model calculates the dimensioning passenger demand so that 95% of the occurrences of a train service on a number of days will have seats enough for all passengers. This parameter is centred around the service that a train operator may provide for the passengers, thus the name.

The dimensioning passenger demand for each train service is the demand between those two consecutively visited stations where the passenger demand (calculated according to comfort level or service level) is the highest. As mentioned, some stations may be disregarded in the process.

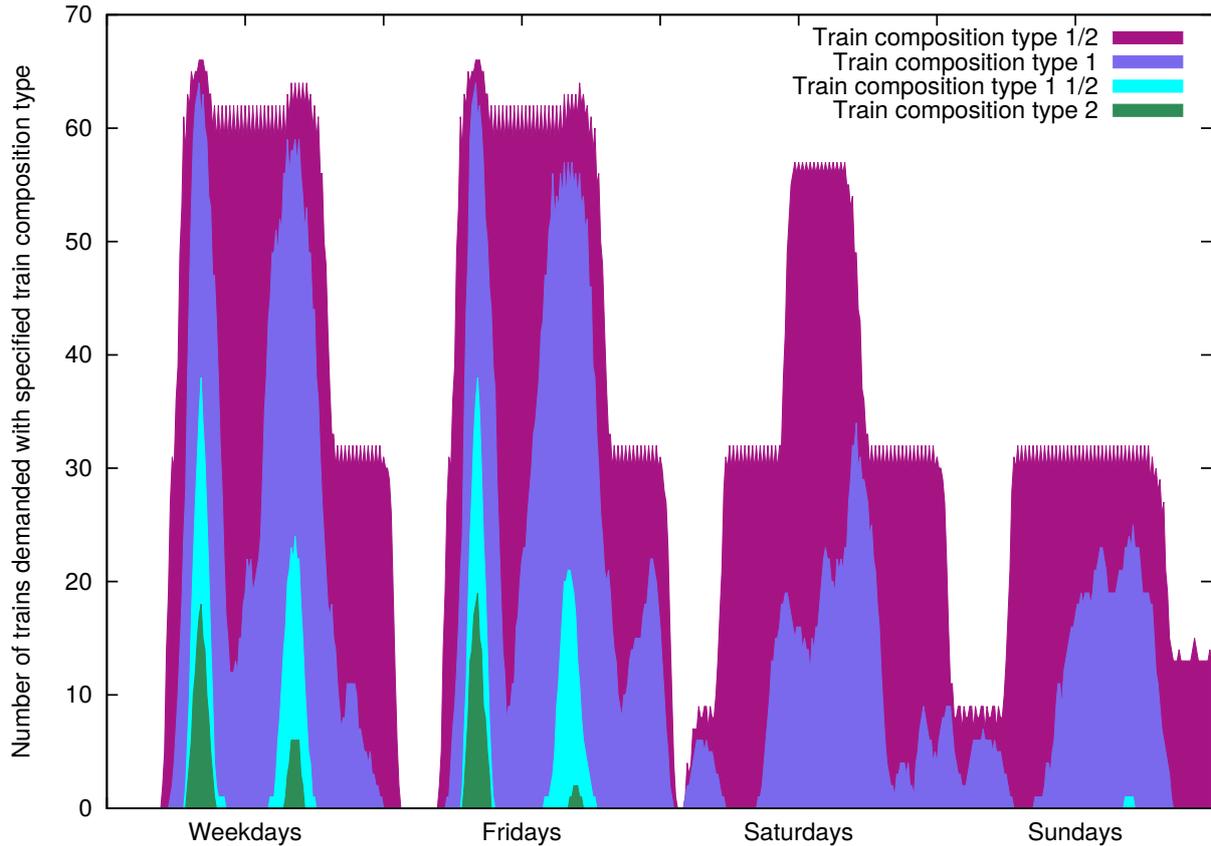


Figure 5: Passenger demand by day type and time expressed as demand for number of specific train composition types, as defined in table 6 on page 21. The composition types are stacked in the figure, their common total indicating the total number of train services in service by day type and time. The suboptimal train composition type $\frac{2}{2}$ is not shown.

Figure 5 shows a graphical representation of current passenger demand data. Here the passenger demand is converted to train composition type according to the seat capacity of the individual train unit types, see table 6. As may be seen from the figure, the train composition type 2 with the highest capacity is only demanded in the rush hours on weekdays and Fridays. The same goes for the train composition type $1\frac{1}{2}$, the train composition type with the second highest capacity, the only difference being that a few train services at Sunday afternoon also demand this kind of composition.

When comparing the demand for the composition $\frac{1}{2}$ in figure 5, to the amount of short train units available to DSB S-tog as shown in table 5, page 20, one can see that the demand for half-length train units is often much higher than the number of half-length train units available. In most of these cases DSB S-tog is forced to assign full-length train units to the train services thus providing excess seat capacity and having to bear the extra cost.

Since 2010 it has been free of charge to bring along bicycles in all DSB S-tog train services. This has meant an increase in passenger demand for flexible space where bicycles may be parked. This is something that rolling stock planning may need to take into account in the future. DSB S-tog is in the process of rebuilding all train unit type 1 train units to also have a large flexible space in the middle of the train unit. In this way the flexible space capacity will be doubled for all train unit type 1 and the

flexible space distribution will be more even in the entire length of train compositions consisting of train unit type 1 train units.

When a rolling stock plan does not provide enough seats to meet passenger demand, the consequences for the train operator are risk of delays due to overcrowding, customer dissatisfaction and customer complaints. All of these consequences may eventually have negative economic implications.

If on the other hand, a rolling stock plan provides too many seats, this also has negative economic implications in that the surplus seats add an extra cost at virtually no extra gain.

Finally, there is also a political demand from society that DSB S-tog maintains an efficient operation. Only by doing so may DSB S-tog gain future transport contracts.

This underlines the importance of having a rolling stock plan that meets passenger demand as closely as possible.

5.1.5 Personnel on Duty

In order to couple and decouple train units and to drive train units into the depot for parking and back to the platform for service, a designated crew of *depot drivers* operate at DSB S-tog. Each depot has a number of depot drivers on duty at different hours of the week, and any rolling stock plan must of course adhere to this number, and not demand more depot operations than it is possible to conduct with the crew on duty.

How many depot drivers are hired and when they should be on duty is decided every time a **standard timetable** is planned (see definition in section 5.1.2), based on the demand in the corresponding rolling stock plan. **Extraordinary timetables** must then adhere to then number of depot drivers hired and their duties for the standard timetable.

Recently, the *train drivers*, that is, the employee group driving train services in scheduled passenger service as well as non-revenue positioning train services, do perform **some** of the operations previously conducted by the depot drivers, for stations Hillerød, Farum, Køge and Frederikssund in the morning and evening on weekends. This also needs to be integrated into the rolling stock planning process.

5.2 Requirements Dependent of the Individual, Physical Train Unit

This section describes the requirements for the rolling stock planning process that are dependent of (that is directly related to) the individual physical train unit. For example, maintenance requirements are related to the individual physical train unit: If a train unit has a break down, then maintenance must be carried out on exactly that train unit.

5.2.1 Scheduled Maintenance

As stated by the Danish Transport Authority, each train unit belonging to DSB S-tog must undergo scheduled maintenance at given intervals.

A standard maintenance check of the individual train unit must be scheduled every 50,000 km of service distance. The duration of a scheduled standard maintenance check is approx. 4 hours.

Table 8: The contractual obligations of DSB Vedligehold to DSB S-tog in 2015 with regards to number of train units to be provided either for the operation or on stand by.

Day type	For operation			On stand by		
	# Type 1	# Type $\frac{1}{2}$	Total	# Type 1	# Type $\frac{1}{2}$	Total
Weekdays	94	28	122	3	0	3
Weekend	54	6	60	3	1	4

In addition to this, minor overhauls of the individual train unit must be scheduled every 100,000 km (for train unit type $\frac{1}{2}$) and 150,000 km (for train unit type 1). The duration of such minor overhauls are approx. 2 days.

Finally, major overhauls of the train units must be scheduled every 600,000 km. These major overhauls have a duration of approx. 1 week.

Figure 6 shows a snapshot of the service distance distribution of the DSB S-tog train units.

On the average, a DSB S-tog train unit type 1 train unit travels a service distance in the order of 500 km a day, a train unit type $\frac{1}{2}$ train unit only in the order of 250 km. However, the service distance travelled may vary a lot from day to day. Some days a train unit of any type may be in maintenance preventing the train unit from running at all. Other days a train unit of any type may only be part of a long train composition in the morning rush hour, and not be running at other times of the day. In that case, the service distance travelled that day by a train unit of any type may be in the order of 50 km. Other days a train unit type 1 train unit may be the part of a train service that is running between Køge and Hillerød stations the whole day, travelling a service distance of the order of 1,000 km. Similarly, a train unit type $\frac{1}{2}$ train unit may travel between Hellerup and Ny Ellebjerg stations the whole day, travelling a service distance in the order of 350 km.

As such, train unit type 1 type train units may enter the 50,000 km scheduled maintenance in the order of every 100 days, SE train units in the order of every 200 days.

At DSB S-tog, the maintenance workshop itself is responsible for requesting the individual train units in for scheduled maintenance. The workshop is organised as a individual company, DSB Vedligehold. Facilities for scheduled maintenance are in Høje Tåstrup.

When a train unit is requested in for scheduled maintenance (or if it has encountered a break down, and needs to undergo unscheduled maintenance, see section 5.2.2), it is the responsibility of the train unit dispatchers (see section 3.2.2) to either get the train unit into the workshop directly (by performing non-revenue positioning) or to make the train unit run on the line passing the workshop (Line B) so as to let the workshop itself pick the individual train unit out for maintenance when it passes by.

Table 8 shows how many train units of the different types must be provided to the operator (DSB S-tog) by the workshop (DSB Vedligehold).

Whenever the workshop gets a train unit in for maintenance (scheduled or unscheduled) it is contractually responsible for delivering another working train unit back to the operator, DSB S-tog if DSB S-tog has the demand for it. As such, the workshop carries the risk of train units breaking down.

DSB S-tog and DSB Vedligehold are currently investigating methods to even out the use of the rolling stock so that the 50,000 km maintenance may be carried out evenly

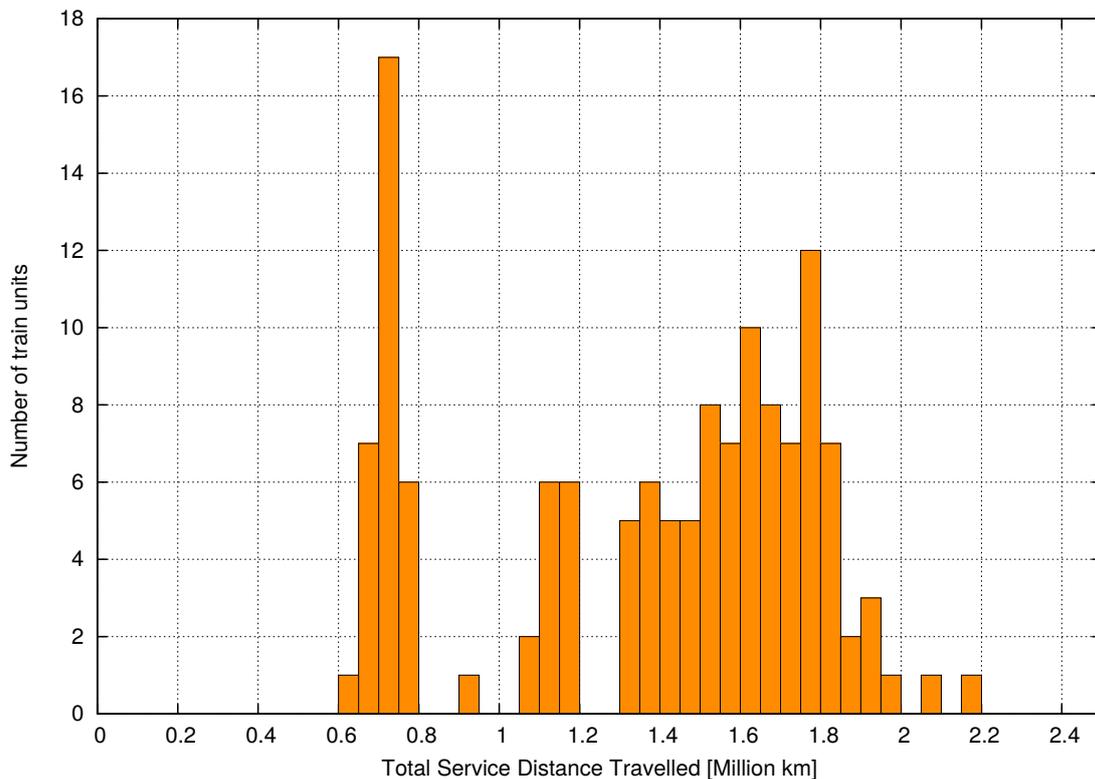


Figure 6: The service distance distribution of the DSB S-tog train units as of January 2013. As may be seen from the figure, the train units form four groups. Starting with the group of train units having the longest service distance (from 2.2 down to 1.3 million km), this group contains the first series of train unit type 1 train units delivered from 1996 and onward. The second group (from 1.2 down to 1 million km) represent the second series of train unit type 1 train units. The third group (from 1 down to 0.8 million km) consists of only one train unit type 1 train unit which has travelled less than the others due to repairs after a collision accident with a truck in 2006. The fourth group (from 0.8 down to 0.6 million km) are the train unit type $\frac{1}{2}$ units, which are utilised differently from the train unit type 1 units and thus travel shorter distances each day.

distributed in time so as not to cause bottlenecks in the workshop. Future rolling stock plans may need to take this into account.

5.2.2 **Unscheduled Maintenance**

Apart from the scheduled maintenance mentioned above, a train unit may break down at any time and require immediate (and thus unscheduled) maintenance. Breakdowns are grouped in one of the following six categories depending on the nature of the breakdown. The time before a break down has to be remedied depends on the category.

- Category A is for breakdowns of major concern, preventing the train unit of continuing in passenger service, e. g. when two consecutive sets of doors are blocked. In this case, in the event of an emergency, the train unit may not be evacuated according to the safety regulations. For this reason it is not allowed in passenger service, and must undergo maintenance immediately;
- Category B is for breakdowns of medium concern needing to be remedied relatively quickly, e. g. when a train unit is externally covered in graffiti. In this category the train unit must undergo maintenance, in this case exterior graffiti removal, within 3 hours;
- Category B1 is for breakdowns of medium concern used when the need for a remedy is less urgent, e. g. a heating system failure. In this category the train unit must undergo maintenance before 0300h the next day;
- Category C is for breakdowns of minor concern needing to be remedied within 72 hours, e. g. one set of blocked doors;
- Category C1 is for breakdowns of minor concern that only need to be remedied within one week, e. g. a compressor fault. The train units have hydraulic brakes independent of the pneumatic system;
- Category D is for breakdowns which have no impairing effect on the functionality of the train unit, e. g. an interior overhead light that is not functioning. Breakdowns of this category can wait until the train unit goes into maintenance for other reasons.

In addition to the main workshop in Høje Tåstrup and the subsidiary workshop in Hundige, DSB Vedligehold also has a mobile repair crew that may head out to remedy broken down train units at any given location at any time.

5.2.3 **Friction Sand**

In order to enhance friction on tracks made slippery by fallen leaves etc., the train units have equipment installed to disperse sand on the tracks in front of the some of the wheels. The sand tanks need to be filled to a certain level, otherwise a category A breakdown of the train unit is registered (see definition section 5.2.2) with an additional speed restriction of 60 km/h. The filling level of the sand tanks must be checked every 10,000 km of service distance.

Friction sand can be refilled at the workshops at Høje Tåstrup and Hundige and new facilities are under selection. The refilling of sand is obstructed by any platform structure beside both sides of the tracks. On the other hand, a surface upon which the friction sand delivering car may drive must be provided on both sides of the tracks, limiting the number of candidate tracks for new facilities. In addition, friction sand must be stored free from frost and humidity.

5.2.4 Exterior Cleaning

The exterior cleaning of the train units is conducted automatically in tunnel shaped cleaning facilities which the train compositions pass through at a speed of 3 km/h. Facilities are in Høje Tåstrup and Hundige.

It is the goal of DSB S-tog to clean the exterior of all train units every 15 days. Since the exterior graffiti removal facility in Høje Tåstrup is on the same track as the facilities for exterior cleaning, this goal can not always be achieved, since the removal of external graffiti has precedence.

5.2.5 Exterior Graffiti Removal

Removing graffiti from the outside of a train unit may take anything from half an hour to an entire day depending on the area of the train unit covered and in particular how much time has elapsed since the graffiti was painted onto the train unit. The time factor is one of the reasons for graffiti being a category B break down (see definition in section 5.2.2). Graffiti removal is performed by DSB S-tog staff in facilities in Hundige and Høje Tåstrup.

5.2.6 Interior Cleaning

The interior cleaning of the train units is performed in on a daily basis in the depots. The cleaning is performed by designated cleaning personnel and also by the depot drivers, both employee groups are DSB S-tog staff. Train units for day train services are cleaned at night and train units for night train services in the morning.

In order to facilitate day to day interior cleaning, a business rule states that train units to enter night time service must be put into service by performing a train composition exchange (see definition in section 5.1.1) with newly cleaned train units. As such, a train composition for a night train service will always consist of newly cleaned train units. A similar business rule states that, in the morning, train units in a night train service must be driven into the depot without being split up. This ensures that train compositions for the day train services are also newly cleaned.

The two business rules are in place to make sure that the cleaning standard is as high as possible at all times and to even out the workload of the personnel cleaning. It is well known that train units with a low cleaning standard attract much more dirt and garbage than train units with a high level of cleanliness.

As of 2012, DSB S-tog is cleaning the interior of the train units according to how much in need of cleaning the individual train units are. This is administered by the cleaning crews themselves in order to achieve employee empowerment. Prior to this, the train units were cleaned according to a schedule.

Internal graffiti is cleaned by DSB S-tog staff and may be performed at any depot.

5.2.7 Winter Preparedness

In order to prevent ice from accumulating underneath the train units in winter time, the undercarriage of all train units must be treated with anti ice fluid every 6 days when the weather is cold. Facilities for doing so are at Høje Tåstrup and København H. The duration of the anti ice treatment itself is one minute for a train unit type $\frac{1}{2}$ and two minutes for a train unit type 1, however due to the track layout, only 6 train units may be treated per hour in each of the two facilities.

5.2.8 Exposure of Commercials

The train units of DSB S-tog all have commercials mounted internally. Some train units also have externally mounted commercials in the form of adhesive foil. In order to expose commercials in certain geographic regions, it may be required that a certain train unit be running on a particular line on a particular set of days.

This may induce the problem of *favourite train units*, that is, train units that the operator may want to have running as much as possible. However, in this way, some train units may run more than others, possibly creating maintenance bottlenecks when the 50,000 km maintenance is to take place at the same time for multiple train units.

5.2.9 Surveillance Video Requests

All train units of DSB S-tog have 24 hour video surveillance. The video recordings of all cameras in a train unit are stored on hard disks in the train unit and may be retrieved for investigative purposes upon order by the Police. At present, the retrieving of recordings takes place in the train unit in which the recording was made. When Police requests a video recording from a particular train unit, this train unit must be driven into the main workshop in Høje Tåstrup for video retrieval within a week from the time of the event the Police wants to investigate. Otherwise the recording is overwritten. In special cases the retrieving of video recordings may be performed by the DSB S-tog mobile repair crew in any of the depots. DSB S-tog is working on a solution to make it possible to remotely download the video recordings in the future, thus making the rolling stock planning free of needing to take this requirement into consideration.

5.2.10 Surface Foil Application

The train units of DSB S-tog are all in the process of being covered by a protective surface foil. This foil has better resistance to graffiti and may, in the event of damage, be replaced much faster and cheaper than the alternative - a conventional repaint of the train unit. In addition to this foil, some train units have a commercial foil applied on top of the protective foil. The commercial foil is replaced at irregular intervals.

Facilities for foiling are in Hundige. The foiling itself is performed by an external company.

5.2.11 Passenger Counting Equipment

Some of the train units, 12 of the train unit type 1 and 4 of the train unit type $\frac{1}{2}$ have infrared passenger counting equipment installed. The infrared counting system is used to count the passengers getting on and off. The data generated is used for modelling purposes. In order to achieve good data samples for modelling, the train units with infrared counting equipment may need to run as specific train services on specific days.

5.2.12 Train Control System Equipment

As of 2014, when the new train control system will be rolled out on parts of the network, special equipment inside the train units will be required to run on the parts of

the network that have the new train control system. Train units not having this equipment installed will not be allowed to run on the parts of the network that are controlled by the new train control system.

6 Further Research

This technical report serves as basis for the further research in the current Ph. D. project.

One topic of further research on automating manual procedures for repairing infeasible rolling stock plans. Based on manual procedures used today by the planners, a simple repair heuristic could be proposed to repair infeasible rolling stock plans made with the current system.

Another topic of further research is in constructing an integrated rolling stock planning model, integrating the subprocesses of the circulation planning, that is, the composition, rotation and depot planning subprocesses.

A potential third topic of further research involves the the prospect of integrating the processes circulation planning and train unit dispatching, processes that are now treated separately at DSB S-tog. This topic may be within scope of the current Ph. D. project and a brief outlook is presented in section 6.1 below.

A potential fourth topic of further research relates to the possible maintenance strategies employed by DSB S-tog inspired from other passenger train operators. This is treated in section 6.2 below, but is considered outside the scope of the current Ph. D. project. However, should the maintenance strategies of DSB S-tog change, this will be a change to the requirements that this Ph. D. will need to take into account.

6.1 Integrating Circulation Planning and Train Unit Dispatching

The idea of splitting the process of rolling stock planning in circulation planning and train unit dispatching at DSB S-tog is probably historically rooted. At the time when planning was conducted using paper and pencil, this may well have been a very good idea, since the circulation plans may have been produced well in advance thus giving the planners the needed time to produce them. Also the structure of the planning can be kept so simple it is easy to conduct, and to inform the involved parties when done.

In the age of automatic planning tools, however, one should ask this question: Does it make sense to make a detailed long term circulation plan stretching a whole month into the future, when reality demands changes to train unit dispatching only a few hours into the plan?

The posit is that if the processes for both circulation planning and train unit dispatching may be automated and integrated into each other, a new, possibly simpler way of performing rolling stock planning may be conducted. In this new form there is no need for the abstraction of virtual train units and the planning horizon may be very short (perhaps even real time). As such, there will be no need for the manual dispatching step of assigning physical train units to virtual ones.

In fact, recent research in related models for airline crew scheduling shows that the cost of a plan may be reduced with up to 9% if the *pairing* step is skipped [7]. The pairing step in airline crew scheduling is analogous to planning with virtual train units for rolling stock planning. Pairing is when individual duties are aggregated to *tours of*

duty. The tours of duty are then assigned to individual crew members. When this step is skipped, the individual duties are assigned directly to the crew members.

The pairing aggregation step has been performed up until now to reduce complexity of the airline crew scheduling problem.

For rolling stock planning, the analogy to skipping the pairing step would be to *directly* assign **physical** train units to **individual** train services, as opposed to assigning **virtual** train units to **aggregated** train services, and then assigning **physical** train units to the **virtual** ones.

Speaking in analogies, one could say, that one can fill more small stones into a bucket if one puts one small stone in at a time, than if one glues together the small stones to big lumps, and then attempts to fit the big lumps into the bucket.

Another aspect is the planning time span. Traditionally, rolling stock planning at DSB S-tog is conducted with a time span of 7 to 18 days, typically. Recent research in related topics (hump yard sorting and scheduling) [2], however, shows that there is only a little gain in producing a combined plan for a longer period as opposed to producing individual, daily plans for each of the days in the given period and letting the finishing conditions of each day form the starting conditions for the calculation of the next.

Speaking in analogies one could say, that only a few problems are “bulldozed” into the future by doing so, and if disruptions are occurring anyway, which they are, the effect of making a plan with a long time span are negligible.

One potential difficulty in integrating rolling stock planning and train unit dispatching processes may occur if only parts of the different processes are automated. If the rolling stock planning process is automated and plans are produced on a very short time horizon, these plans may prove very difficult to handle manually in the case of a disruption, since the plans may not necessarily contain the structures built into the manual plans today making them easy to handle manually.

Investigations must show if the realisation of these ideas of integration (to what ever degree) may prove beneficial to DSB S-tog.

6.2 Evaluating Alternative Maintenance Scheduling Strategies

Different train operators have different maintenance scheduling strategies. Up until now it has been the strategy of DSB S-tog and DSB Vedligehold to use each train unit as long as possible before conducting maintenance for that particular train unit. A train unit thus only enters maintenance when it has been running for 50,000 km since the last time, or of course, if it breaks down before that limit is reached.

When the train unit enters maintenance at DSB Vedligehold, typically nearly every possible maintenance task is carried out for that particular train unit. As such, the train unit may be *as good as new* when it rolls out from the workshop after maintenance. The rationale for this strategy is to keep the number of maintenance stops for each train unit to a minimum. In other words, the strategy is: *Let's fix everything now the train unit is here!*

Other train operators have different maintenance scheduling strategies. At SBB in Switzerland for instance, each train unit is typically maintained after much less service distance [8]. Also the individual maintenance stops are typically shorter than at DSB S-tog. In other words, the strategy is: *Let's fix what we can when we can!*

Using this strategy, the train unit may not at all be *as good as new* when it leaves maintenance, however since the general level of maintenance of all train units is higher

(since the time since each train unit has been looked over is much shorter), the posit is that fewer break downs are encountered.

Other train operators again may have different conditions that influence their maintenance scheduling. At DB S-Bahn Berlin, maintenance may be scheduled after as little as 600 km (compared to that of 50,000 km at DSB S-tog) due to technical issues with the rolling stock [6]. Making feasible rolling stock rotation plans under such conditions may well be quite a challenge.

Investigations must show if another maintenance scheduling strategy following a different rationale than today may prove an advantage to DSB S-tog.

Acknowledgements

The current Ph. D. project is supervised by Professor Jesper Larsen, DTU, Julie Jespersen Groth, DSB, and Marco Laumanns, IBM.

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