Schiphol's dynamic traffic management

A case study on rescheduling

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Challenge the future

Schiphol's dynamic traffic management

A case study on rescheduling

by

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Delft University of Technology

Preface

This master thesis has been written within the educational program of the Master of Civil Engineering at the Technical University of Delft. It is the final product of the followed master track 'Transport and Planning'. The research has been made under the authority of NS Hispeed.

My thesis consists of a case study on rescheduling in the Schiphol area by means of dynamic railway traffic management. Chapter 1 gives an introduction and overview of the problems related to the research. Results of the literature review can be found in chapter 2. In the third chapter more background information on the possibilities in railway traffic management are found. Information about the model and the results can be found in respectively chapter 4 and 5. This thesis end with a conclusion and recommendations.

In particularly I am pleased to thank NS Hispeed, ProRail, NS and RIGD-LOXIA for providing me data and support in any other way. Furthermore I want to thank all supervisors for their helpful and constructing input during the graduation project.

A special thanks to Sanne, who always supported me under all circumstances.

Nicolaas de Vries
Zürich, April 2014

Executive Summary

Schiphol's dynamic railway traffic management

The railway station of Amsterdam Airport 'Schiphol' is a very busy one. In the surroundings of this station, the traffic is controlled by an automated system: a so-called "Dynamic Traffic Management System" or DVM system in Dutch. This system was introduced in 2007 to use the capacity of the tracks in a more efficient way and to enlighten the task of traffic controllers. Future developments in the service pattern of the operators and improvements of the nearby infrastructure cause this system to become partially obsolete. With some improvements a similar system can still control the railway traffic in the area. The options for such a system are being explored in this research.

The current situation (2013) already shows some signs that the capacity in the tunnel will be reached soon. The current 22-24 trains an hour cause minimal margins in driving time. The role of DVM in stable railway operations is not directly clear. A report of the performance analysis department about the performance of trains of NS Hispeed in the first month of the timetable of 2013 shows some indications that delays occur regularly around the Schiphol area. The analysts concluded that most of these delays are secondary delays as the trains are hindered by other trains. In some cases they also mention that the DVM plays a role in the delays as well. The reason can be found in the algorithm of the DVM, which is (on purpose) kept simple.

Since the lay-out (figure 2) of the Amsterdam Riekerpolder Aansluiting and the so-called 'Zuid-as' will change between 2015 and 2018 the DVM needs to be reprogrammed as well. Based on the earlier findings one could question whether the actual system is still able to fulfil its tasks efficiently in the future or not. Maybe an improved system could be more suitable for this junction. Several indicators for this can be found. The main one is that the actual system doesn't make a difference in train characteristics which results in equal priorities for trains with totally different destinations and dwell time characteristics. Also the intention of the NS to offer synchronised Cross-Platform transfer connections plays a major role as the classical DVM cannot cope with this. The problem is illustrated in figure 1 and leads to the following question:

Research question:

- *What DVM concept utilises the capacity of Schiphol railway station and surroundings the most efficient for the infrastructure lay-out and timetable of the near future?*

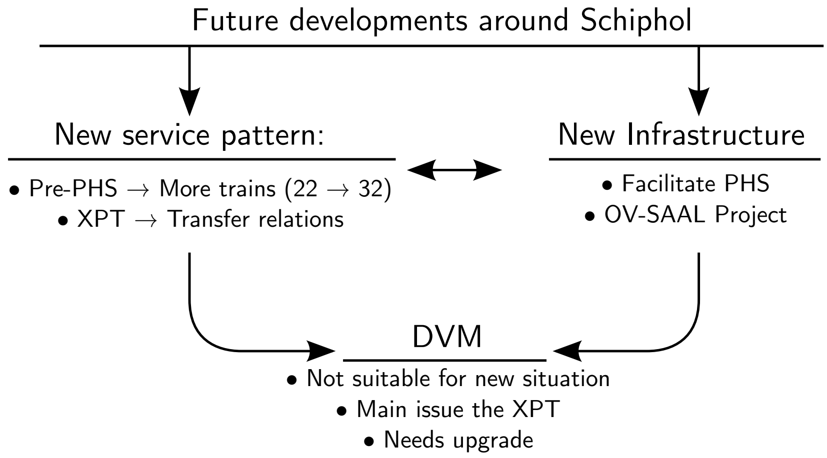


Figure 1: Diagram of the problem with the actual DVM system.

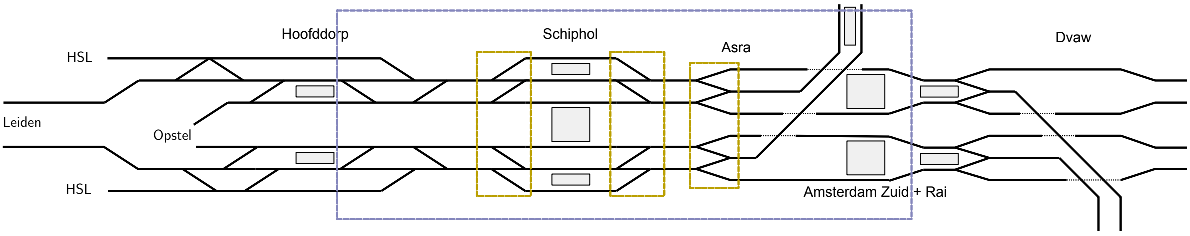


Figure 2: Overview of the 2018 Schiphol railway network. The large, blue area shows the control area of the DVM system. The smaller, orange areas show the steering areas.

Dynamic railway traffic management requires rescheduling. Rescheduling in railway traffic management exists of three different components: reordering, rerouting and retiming. There are several combinations possible for these DVM-tools, resulting in different alternatives. All random combinations can be thought of, but not all make sense. Reordering for example is a crucial part of the system. The DVM could not function properly without it in case of perturbations. Because in case of merging trains, one of them would have to wait for its predecessor when that train is running late. The remaining solutions are combinations of reordering with the other rescheduling tools. All the combinations tested are visible at the results in table 1.

The experiment

By simulating the railway traffic of the Schiphol area in OpenTrack (railway traffic simulation software) one can find out which combination of the rescheduling components is the most optimal for this case. The performance indicators consist of the smallest average delay of a train caused within the model, the train with the maximum delay, and the amount of cross-platform transfers kept. A further wish is that the system needs to be understandable for signallers, so that decisions made by the system can be easily understood.

The input data for the model consist of the following: converted infrastructure data from ProRail[1], rolling stock data, the timetable (which is assumed in this research) and initial delays. All other parameters like dwell times and driving performance of trains are approximated by calibrating the model in a tough and complex validation process. The simulations consist of 30 runs per DVM concept, each with 3:10 hours per run, with a total simulation time of one hour per alternative.

[1]Dutch national rail infrastructure manager

Results and Conclusion

All alternatives are tested on their performance which consists of three indicators: average delay, maximum delay and the amount of cross-platform transfer (XPT) connections kept. The first two are measured by measuring the delay at the beginning and end of the model and by measuring their de-/increase. The outcome of this delay is corrected for delays that already were present in the run without stochastic variables and initial delays. This eliminates the most of the effects of poor scheduling. Also the maximum delayed train (over the 30 runs) is recorded. The cross-platform transfer connection is only maintained if the maximum waiting time of a train does not exceed the threshold waiting time (3 minutes). The rate of trains which maintains this transfer is a performance indicator as well.

Table 1: Overall results of the simulation, sorted by average delay.

Rescheduling elements	Average delay [s/train]	Max. delay [s]	XPT connections kept [%]
Biggest Delay-Rerouting	60.2	692	79.4
Biggest Delay-Rerouting-Retiming	69.1	829	69.7
Biggest Delay-Retiming	70.2	830	69.4
FCFS-Rerouting	85.3	1531	76.9
Biggest Delay	85.7	1004	78.6
FCFS	87.3	1184	80.3
Destination	90.9	1132	78.3
Train Type	94.8	1132	76.1
FCFS-Rerouting-Retiming	102.5	1150	68.1
FCFS-Retiming	107.7	1244	69.4

After simulating all the DVM concepts the above results show that the best combination consists of reordering - prioritising by biggest delay of a train - and rerouting. This allows the train with the largest delay go first in case of a conflict. The rerouting allows for flexible track usage at Schiphol, as is the case today for example. This utilises capacity in the bottleneck Schiphol more optimal. Today's first come first served prioritisation regime scores also reasonable compared with the biggest delay algorithm. The combinations with the other rescheduling elements (rerouting and retiming) are however less successful.

The relation between the cross-platform transfer connection waiting times and the delays in the DVM area is also tested. It shows that it is wise to keep waiting times low, as the system can get very unstable in case of long waiting times.

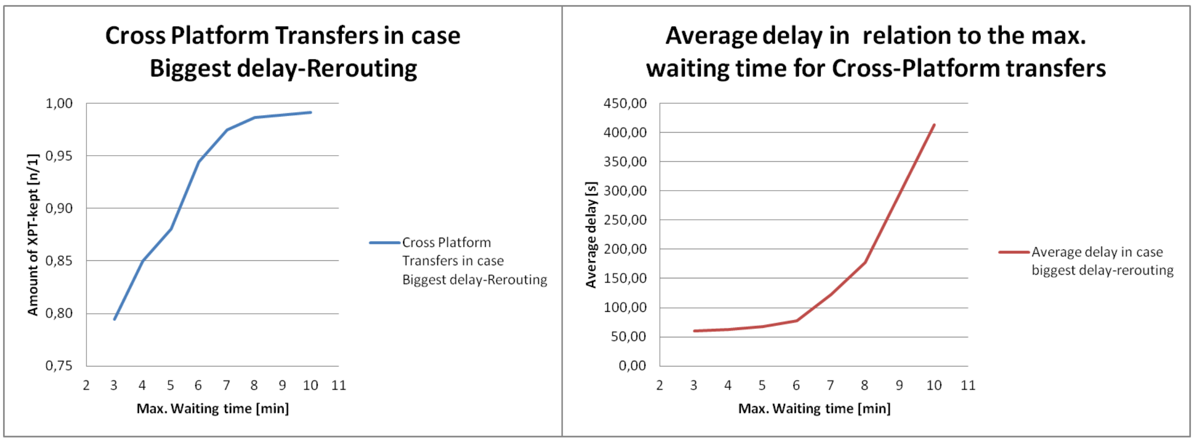


Figure 3: Showing the relation between the amount of XPT-connections kept and the XPT maximum waiting time (left), and the relation between the average delay caused in the system and the XPT maximum waiting time.

Contents

Chapter 1

Introduction and Problem Statement

The railway station of Amsterdam Airport 'Schiphol' is a very busy one. In the surroundings of this station, the traffic is controlled by an automated system: a so-called "Dynamic Traffic Management System" or DVM system in Dutch. This system was introduced in 2007 to use the capacity of the tracks in a more efficient way and to enlighten the task of traffic controllers. Future developments in the service pattern of the operators and improvements of the nearby infrastructure cause this system to become partially obsolete. With some improvements a similar system can still control the railway traffic in the area. The options for such a system are being explored in this research.

1.1 Railway system in the Netherlands

The Dutch national railway network is a state of the art system while being one of the busiest in the world with over twenty thousand train-kilometres per year per kilometre of track (ProRail, 2012). The network can be characterised as a high frequency system with a clear periodic timetable which consists of a 30 min. interval per train type per line on the largest part of the network. The tracks are managed and maintained by ProRail which is fully owned by the Dutch national government. ProRail is responsible for the safety and route setting on the tracks. The company does this by means of traffic control with signallers at thirteen locations throughout the country.

There are multiple railway operators on the Dutch tracks. However only one (NS) is responsible for the main lines throughout the country. NS is the Dutch national railway company (Nederlandse Spoorwegen), which operates on most railway corridors in the Netherlands. They operate primarily without state subsidies, although all shares are still owned by the state. One can define three kinds of passenger services on the Dutch railway network: International/High Speed, Intercity and Sprinter/Local. The first only calls at major cities along long distance corridors, mainly crossing national borders with an interval of once every single or two hours. The second calls at every city and also the bigger secondary stations of those cities. Sprinters and local trains simply call at all stations. In table 1.1 an overview of some railway facts of the Netherlands is given.

1.2 Schiphol railway station and surroundings

Amsterdam Airport 'Schiphol' is situated just south west of Amsterdam and has a subsurface railway station. In contrast with most airport railway stations, Schiphol is not only hosting one or more airport lines but is also an important hub in both the national and international rail network itself. Due to the integration of multiple transport modes at the airport, the railway station ends up being one of the busiest in the Netherlands with over 600 trains daily, resulting in a maximum of 22-24 trains per direction per hour (NS, 2013). The station is reaching its capacity limit concerning the handling of amount of trains. Schiphol has become already a real bottleneck. As the station is underground, the

Table 1.1: Facts about the Dutch national railway system (NS, 2012a; ProRail, 2012)

Facts about the Dutch national railway system		2012
Passenger kilometres (NS only)	[pax./year]	16 808 000 000
Train kilometres	[km/year]	150 000 000
Length of network	[km]	3 063
Kilometres of Track	[km]	7 033
Track usage	[trains/km/year]	21 328
Stations	[-]	404
Switches	[-]	7 195
Punctuality <5 min.	[%]	94.2
Railway Operators	[-]	28

space is limited and therefore efficient use of the tracks is needed to avoid costly expansions of the infrastructure.

(a) Geographical overview of the Schiphol area (openstreetmap.org).

(b) Visualization of scheduled train lines in 2013. Every line has a 30 min. interval (NS).

Figure 1.1: Schiphol area visualizations.

1.2.1 Topology

Schiphol station is located just west of a junction – Amsterdam Riekerpolder Aansluiting (Asra) - where two double-track railways merge and continues as a four-track tunnel underneath the airport. The railway station of Schiphol has six tracks itself with three double-sided platforms. Just south west of the tunnel one will find Hoofddorp with a local station, an important coach yard, and the start of the dedicated high speed line in direction of Rotterdam and Paris. The Topology is visible in figure 1.2 and in more detail in appendix C .

1.2.2 Future

In the near future the junction Amsterdam Riekerpolder Aansluiting (Asra) will be transformed as part of the 'OV-SAAL' project (Schiphol, Amsterdam, Almere, Lelystad). This project will enlarge the accessibility of the cities along the SAAL corridor by improving the rail network. Schiphol, Amsterdam, Almere and Lelystad, will benefit from these measures by having more frequent and robust railway connections. Asra nowadays is a junction at level with four switches per direction. To change tracks, a crossing movement is necessary. The conflicts initiated by the crossing movements make the junction a bottleneck, as being illustrated in red in figure 1.3. For example: if from all directions half of the trains would have to change tracks, these pieces of track would have to deal with 75% of the trains. This limits capacity and is a major reason for the planned improvements on this junction. Trains driving

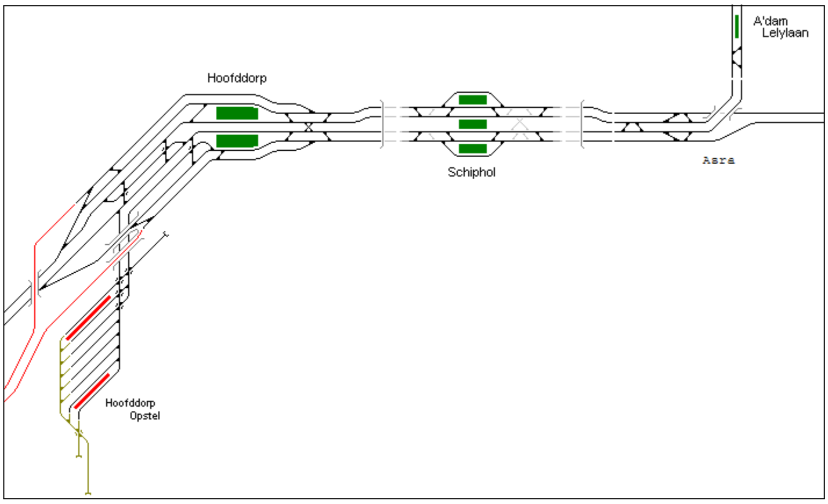


Figure 1.2: Topology of the Schiphol area (sporenplan.nl).

in opposite directions cross each other without any conflicts by means of a fly-over (ProRail, 2013b). Or in other words: both directions can function independently.

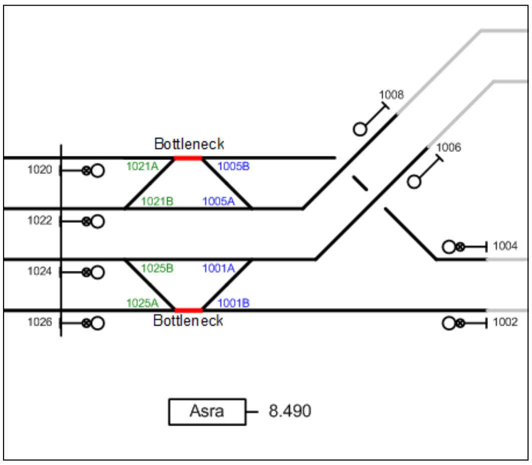


Figure 1.3: The 'ASRA' junction in 2013 (sporenplan.nl).

To minimize conflicts the Asra junction will be upgraded to a double fork junction. This means that the branches of the fork diverge already before they merge. In this way trains pre sort to be on the right track in advance. As a result trains from both branches can reach both parallel tracks without any crossing conflicts and vice versa, as long as they are not heading for the same track. By eliminating those conflicts the capacity of the junction will be increased, which leads to a more robust train service and the possibility to push the frequency even to a higher level. On the eastern branch ('Zuid-as') of Asra, tracks are also planned to be doubled from double to quadruple track. This will result in the earlier mentioned 'diverging before merging', taking place a bit further to the east.

1.3 DVM

The dynamic traffic management (Dynamisch VerkeersManagement or DVM in Dutch) system is a concept which functions as an automated device, taking over some tasks of the signallers. This means that in normal service and even during small disruptions the signaller doesn't have to do anything at all. Where in the old days routes were set manually by signallers, since 1999 the routes are set automatically by 'ARI' as long as a train does not have a major delay. As soon as delays are getting larger, signallers

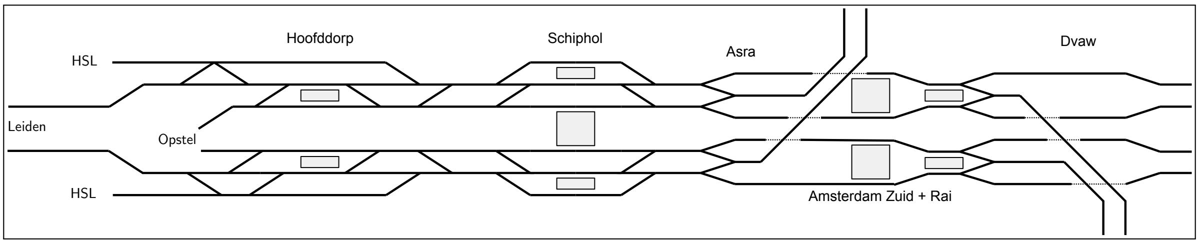


Figure 1.4: The 'ASRA' junction and surrounding tracks in 2018.

have to take over the controls with the regular system. This leads - especially in busy areas - to a heavy workload for them and a less efficient use of capacity. Besides that, the high frequencies (up to 24 trains an hour) cause the system being very vulnerable for disruptions (Schaafsma, 2006). Therefore DVM was introduced in 2007 at the railway station of Schiphol. The DVM consists of multiple aspects which are all implemented as rules of an automated controlling device. The following aspects form today's DVM:

- First Come First Served (FCFS)
- Cross-Platform Switch (XPS)
- "Keep Your Lane"

The three mentioned functions are all designed to encourage the circulation of railway traffic or in other words to use capacity efficiently. The exact functioning can be found in the official documentation of the DVM system in appendix D. A brief explanation of the measures follows below.

1.3.1 First Come First Served

Due to merging of tracks on both ends of Schiphol, conflicts can occur when trains are scheduled tightly and therefore small delays might be present. Ignoring the planned order the DVM decides which train is handled first based on a simple rule. Trains are handled with the FCFS principle with the use of trigger points where the train's presence is automatically notified by the system. A train passing such a trigger point earlier then a potential conflicting train will get its route set first. This holds for trains going in the direction of Schiphol, but also for trains leaving Schiphol encountering conflicts before diverging in several directions. Local trains heading for Amsterdam CS are corrected by adding up a 100 second 'penalty' to the time stamp (at the trigger point) to avoid intercity trains ending up behind slow local trains. Besides this correction mostly the First In First Out (FIFO) principle is used as well. FIFO does not only serves the first train first, but will also make sure that this train leaves the system prior to the other. This results in all trains generally being handled equally independent of the characteristics of the boarding of passengers.

1.3.2 Cross-Platform Switch

To optimally use platform capacity the outer tracks of Schiphol use both sides of a single platform. This results in that a train on such tracks can arrive at two sides of the platform, increasing capacity as trains can call at Schiphol next to each other. This is however seen at most railway stations. The revolutionary part is that one doesn't know in advance on which side of the platforms the train arrives. The DVM directs a train to the platform side the previous train wasn't sent to, fully automatically. Passengers will only know a couple of minutes in advance (five officially) on which side of the platform their train will arrive. In this way trains are efficiently lead through Schiphol reducing hindrances from trains driving behind each other. This way of railway traffic management is called the 'Cross-Platform Switch', abbreviated as XPS.

1.3.3 "Keep your lane"

Optimizing a railway traffic flow one could refer to fluid mechanics where one prefers to keep the flow as laminar as possible to avoid the resistance turbulence generates. In railway traffic one could see this as avoiding conflicts in train routes, especially in bottlenecks. This can be accomplished simply by routing trains straight through the Schiphol tunnel without any changing of 'lanes'. This means most existing switches inside the tunnel will generally not be used except the four switches needed for the XPS. The keep your lane principle also partially exists here due to the wish of the operator to inform the passengers in time on what platform they have to be.

1.4 Problem

The current situation (2013) already shows some signs that the capacity in the tunnel will be reached soon. The current 22-24 trains an hour cause minimal margins in driving time. The role of DVM in stable railway operations is not directly clear. A report of the performance analysis department about the performance of trains of NS Hispeed in the first month of the timetable of 2013 shows some indications that delays occur regularly around the Schiphol area. The analysts concluded that most of these delays are secondary delays as the trains are hindered by other trains. In some cases they also mention that the DVM plays a role in the delays as well. The reason can be found in the algorithm of the DVM, which is (on purpose) kept simple.

Since the lay-out of the Amsterdam Riekerpolder Aansluiting and the so-called 'Zuid-as' will change between 2015 and 2018 the DVM needs to be reprogrammed as well. Based on the earlier findings one could question whether the actual system is still able to fulfil its tasks efficiently in the future or not. Maybe an improved system could be more suitable for this junction. Several indicators for this can be found. The main one is that the actual system doesn't make a difference in train characteristics which results in equal priorities for trains with totally different destinations and dwell time characteristics. Also the intention of the NS to offer synchronised Cross-Platform transfer connections plays a major role as the classical DVM cannot cope with this.

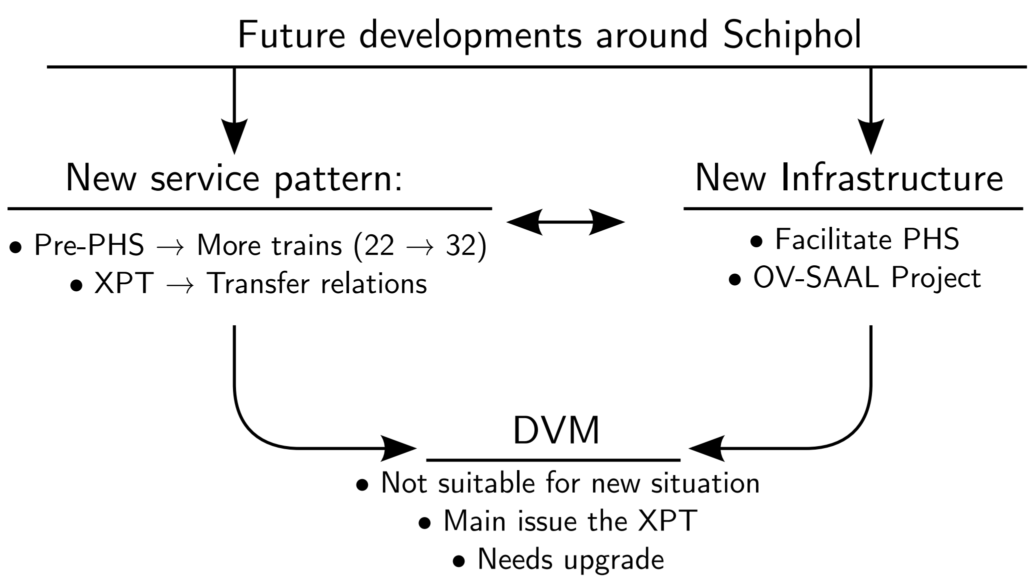


Figure 1.5: Diagram of the problem.

1.5 Research

Based on the problem a research objective can be stated:

Research objective:

- *Develop and analyse feasible, improved DVM concepts for the station of Schiphol airport for the near future.*

To accomplish this objective one wants to work clearly structured by asking themselves a research question. For this case the main research question can be formulated as follows:

Research question:

- *What DVM concept utilises the capacity of Schiphol railway station and surroundings the most efficient for the infrastructure lay-out and timetable of the near future?*

By asking this research question several other questions arise which need to be answered first. They are formulated below.

Sub-questions:

How does today's DVM works?
How will railway traffic and infrastructure lay-outs develop in the future around Schiphol?
How does one measure the performance of a dynamic railway traffic management system?
In what way can one prioritise trains?
Which dynamic railway traffic management system systems are nowadays already used?
Which requirements to a dynamic railway traffic management system are requested by stakeholders?
What is the performance of today's dynamic railway traffic management system?
What dynamic railway traffic management system strategy performs best in the future situation?
What is the improvement relative to the old dynamic railway traffic management system?

1.6 Methods

To answer all the research questions several methods are needed. To fulfil the research in a structured way one also needs to structure the methods used in it. For this the following model is formulated.

1.6.1 Research Approach

Firstly information is gathered in several ways. This information is used to identify the problem and find feasible solutions, which are the different DVM's for the future. From this point on one can do simulations to find out the best solutions. Based on this one can draw their conclusions. The research methods are described below and the relations are illustrated in figure 1.6.

1.6.2 Literature

In order to avoid duplicate research and to receive basic level of knowledge in the subject, literature is reviewed. To come to new knowledge it is needed to come to the border of existing research which is described in journals, papers, books and etc. Furthermore it creates an objective starting point of

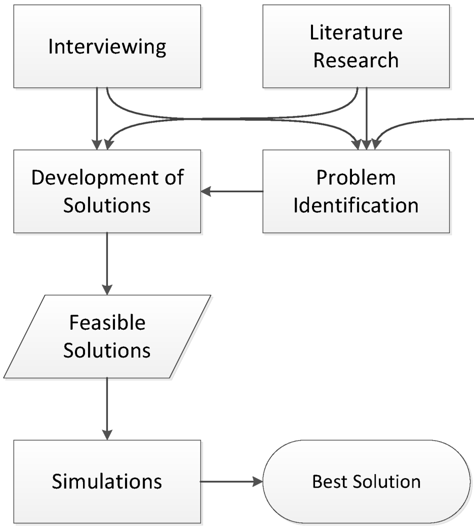


Figure 1.6: Research approach.

a solid research to avoid tunnelvision. It also helps to get familiar with proven research methods and any advantages or disadvantages of them.

In railway science a lot of development is being done internally at railway companies which is being published very scantily, partially because of confidentiality. Only research published at conferences or done by academic institutes is easily found. Theoretical frameworks however are published thoroughly as they are mostly developed by engineers and mathematicians of railway oriented departments of major universities in Europe. It often lacks the practical proofs, especially in dynamic traffic management solutions, since there is only one example of a real DVM.

1.6.3 Interviews (with main stakeholders)

As literature will not give answers to all questions about the dynamic railway traffic system, internal information is needed. To get to know the experiences of today's system, people working with it might want to give their opinion on it. They know the system inside out and might experience shortcomings which can be relevant for the research. By having interviews with employees of both the infrastructure manager and the railway operators, requirements for a new prioritization strategy can be formulated. The interviews also allow retrieving important data and information about both the actual and future state of the infrastructure and the operator's schedules. This way one can work with confidential but necessary fundamental information for the research. By doing so, the subject can be understood thoroughly which is an addition to the theoretical parts of the research.

1.6.4 Data collection

For this research data is needed in different forms. Firstly, information from ProRail's InfraAtlas is needed as input for simulation as it accurately carries all infrastructure data, varying from locations to default routes. It contains various datasets of the whole country. Furthermore train characteristics are needed which are measured around Schiphol. For example the stochastic process of passengers boarding a train and the distribution of the delays of trains when they enter or leave the part of the network which is being analysed. These are monitored in several ways by ProRail's performance analysis department, and can be requested internally.

1.6.5 Simulations

For simulating railway operations there are several possible applications available worldwide. ProRail has their own software available for railway simulations, but is only used by themselves. The most widespread used software in Europe by academic institutes and railway traffic consultants is OpenTrack. This software is originally developed in Zürich at the Swiss Federal Institute of Technology (ETHZ) but is now an independent spin-off. OpenTrack allows sophisticated simulations of railway operations while automatically measuring all necessary statistics of these operations (Nash and Huerlimann, 2004). The software can import infrastructure data from RailML, the relatively new international railway specifying language. ProRail's InfraAtlas data is unfortunately not written is this standard as it is normally needed solely for internal use. To make it compatible with OpenTrack there is a workaround available which converts data to the RailML standard using IA2OT. However this piece of extra software has its limitations, it is sufficient for simulation purposes after some manual corrections (Tax, 2011). Simulations will be done in three different configurations, depending on the time (section 1.7.1). The simulations of 2013 are solely to validate the model for scientific purposes. More about this is to be found in chapter 4.

1.7 Restrictions

To fix the focus of this thesis certain restrictions in the research project are applied. Mainly because the time is limited to perform the research and to ensure feasible simulation times. The main aspects of the restrictions are those in time and space. Also the possible solutions are restricted.

1.7.1 Time frame

ProRail already has a short term research project going on to solve the problems for the situation in the near future (2014-2015). The focus of this research will therefore be the period after that meaning 2018 and later. This date is mainly chosen as then the infrastructure and train schedule should be fully developed according to today's plans. After 2018 is also referred to as Pre-PHS, a time period before PHS where already high frequencies will be offered to passengers. PHS is a plan to drive a metro-like service pattern in the Randstad, originally planned for 2020, and now slowly postponed to a later moment. The 2013 situation will be used for validation of the model.

1.7.2 Geographical

To avoid unnecessary complexity not the complete railway network of the Netherlands will be simulated. Only the most important parts are used as this reduces calculation times and avoids modelling of unimportant parts of the model. To keep everything realistic, stochastic data of delays of trains is needed at the borders of the model. Without this it would assume all trains outside the model drive on-time which is highly unlikely. The specific area mentioned will be as far as the automated system needs to know where the trains is. Probably this is on the east side already at Duivendrecht, northbound around Lelylaan, Southwest a couple of blocks before the HSL junction, both on the HSL and the conventional track. This is roughly the area visible in figure 1.1a.

1.7.3 Solutions

The best solutions possible for a new DVM system could possibly mean that 10 signallers should work at the Schiphol area and do everything manually. As this is a possibility but fairly unfeasible these solutions are not mentioned. Only automated DVM strategies are researched tested in this research. The pros and cons of such a system will be elaborated on in the next chapter.

Chapter 2

Theoretical Framework

In this chapter some railway fundamentals are explained. This will start at the very beginning elaborating on signals and the block system; slowly this will progress to the research which leads to the development of Schiphol's DVM system. Main topics will be **capacity, safety, robustness and performance measurement**, which form the core of **railway scheduling and operations**. Stochastic influences will be discussed as well.

2.1 Railway capacity and safety

The capacity of railways depends on several constraints and can be viewed to in different ways. Therefore it is hard to define capacity in a single sentence. UIC code 406 "capacity" tries to explain it as follows:

> The capacity of any railway infrastructure is:
>
> - *the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively and the infrastructure manager's own assumptions;*
> - *in nodes, individual lines or part of the network;*
> - *with market-oriented quality.*
>
> This must also take account of the infrastructure manager's own requirements.
>
> (UIC, 2004)

The first two points refer to theoretical, physical capacity. The third however relates to reliability and service patterns, an important issue which will be discussed in section 2.2.

To understand how the capacity can be determined in railway traffic it is wise to start with a single line with one-way traffic, which makes it easy to understand how safety and capacity are intertwined. To keep trains separated and therefore operate safely, the block system is used mostly around the world.

2.1.1 The block system & signalling

To ensure safety on the tracks one must be sure that only one train wants to use the same infrastructure at a time. In order to facilitate this, the tracks are divided in so-called blocks. They typically have the length of the braking distance of a train plus some margin (Hansen and Pachl, 2008). Blocks should only be occupied by a train when one can be one hundred percent sure that the block is empty. To guarantee this one must prove the following two things. Firstly the previous train must have left the block and secondly that train's integrity must be proved. In the block system there are several ways to do this; the main two ways are axle counters at beginning and end of a block or an electrical closed circuit system. As they make sure there is no vehicle on the tracks both of the requirements are fulfilled and trains can operate safely while separated.

To inform the train driver whether a block is free or not, signals are used to show an aspect. In the Netherlands this could be red, yellow or green, optionally flashing in some circumstances and in some cases a speed indication number below it. The main idea is that when a signal shows red, one has to stop in front of it. Since trains have a fairly long braking distance, the signal one block before the red signal will show yellow. This indicates that the train driver should start braking as the blocks are generally larger than the trains braking distance. This is the general principle, the actual signals are described in figure 2.1.

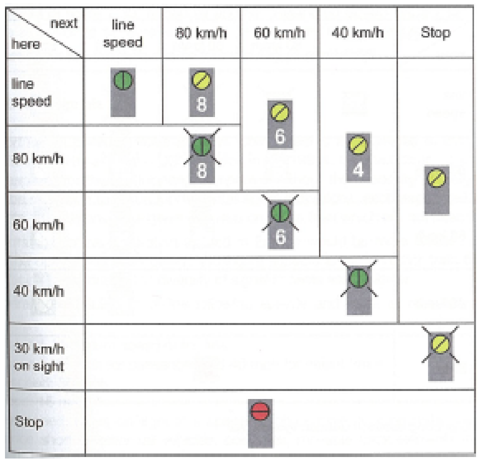


Figure 2.1: Dutch signal system by Pachl, J. in (Theeg and Vlasenko, 2009).

For unhindered train operations it is required to have at least two free blocks in front of a train as this means the encountered signal will show green under normal circumstances. To mathematically determine the capacity of the open track this fact is used. One can calculate the time that a block is occupied by a single train as soon as one knows the block lengths, train length, driving speed(s) and some smaller additions like sight, reaction and switching time (Goverde, 2005; Hansen and Pachl, 2008; UIC, 2004). This is illustrated in figure 2.2. In the scheduling phase trains are planned in such a way that they should never need to stop in front of a red signal while being underway from station to station (ProRail, 2013a).

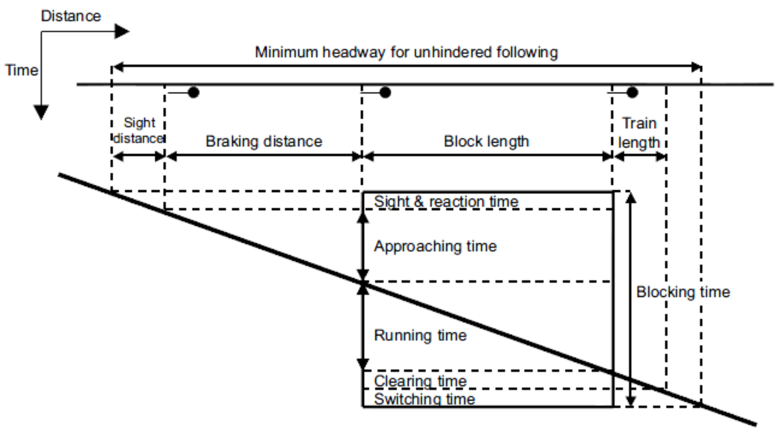


Figure 2.2: Blocking time for fixed block signalling (Goverde, 2005).

By knowing the time necessary for the unhindered movements of a single train through a block, one can easily derive the amount of trains per hour which could theoretically pass the block without slowing down. As the typical signal block length on the Dutch open tracks is about 1800 meters, with a speed of 140 km/h one could calculate a capacity of roughly one train every 100 seconds which is 36 trains an hour. There are however some other aspects to be taken into account to determine the real capacity. These can be found at the places where one enters or leaves the open track, which are stations and junctions. But also margins need to be taken into account as almost no train is running punctually on the second[1]. These margins or also called buffers, and should avoid knock-on delays. This is further explained in section 2.2.

2.1.2 Bottlenecks

The bottlenecks in a railway system can be found around junctions and stations. Here trains are not running at high speeds and could have conflicting routes. Platform capacity is often also an issue as trains need a dwell time which should be long enough to let passengers disembark and board the train. Especially intercity and international trains at major stops need a serious amount of time. This is due to the characteristics of the passengers - carrying large bags, not travelling daily, etc. - and the train - smaller and less doors than commuter trains, reserved seats, etc. Where commuter trains mostly do not need more than 30 seconds, an international train can easily need about three minutes for the process. Using 2-3 minutes, plus a surplus for the approach, clearing and switching time, one can realize that the capacity of a platform track is drastically lower than those of the open tracks.

To assure safety on the tracks, schedulers plan conflict free. If all trains would run perfectly on time trains wouldn't even hit each other without signals. This could be seen as the first layer of safety in railway traffic before the signalling and ATP[2] system. By even adding some extra safety margin on top of this one gets the planning standards which are formulated and applied by ProRail in the Network Statement (ProRail, 2013a). These standards are used for planning in bottlenecks and concern both safety and capacity. For rescheduling practices these rules are not applied (yet) and in combination with a DVM it is not possible to apply these standards at all. The standards are described in the norms in table 2.1.

Table 2.1: Planning standards which are mostly not used for (automated) rescheduling (ProRail, 2013a).

Standard	Description	Value
Departure-Departure	From different tracks to the same track	3 minutes
Through-Through	Two trains following each other up on open tracks	3 minutes
Arrival-Arrival	From the same track to different platform tracks	3 minutes
Departure-Arrival	Same platform track	4 minutes
Departure-Departure	Same platform track (short stop)	4 minutes
Departure-Through	Same track (e.g. local train followed by IC)	4 minutes
Arrival-Through	Overtaking	2 minutes
Through-Departure	Overtaking	2 minutes
Minimum crossing times when not calculated		
Diverging		3 minutes
Arrival-Departure	In opposite directions	1 minute
Departure-Arrival	In opposite directions	6 minutes

These standards give an indication of the time being lost if trains have to share infrastructure. Especially on the larger stations like Utrecht Centraal, Amersfoort, Zwolle or Eindhoven where lots of trains are coming from various directions. Crossing corridors lead to regular crossing movements which cause the capacity to drop. It is recommended to avoid unnecessary level crossings of trains, especially when high-frequency corridors are involved to increase capacity and punctuality. This is called the unravelling of lines (Weeda and Hofstra, 2009). Unravelling does influence the service offer of the operators, because they want to serve the passengers high frequencies but also direct connections. To offer both of them, cross-platform transfers are introduced, which is problematic to combine with the unravelling of lines and/or corridors as extra crossing movements have to occur. Here ProRail and NS both face a different side of capacity. ProRail's main priority is the physical capacity and NS wants to offer market conforming services. This conflict is further elaborated on in section 3.1.3.

[1] Japan however is actually really good at this.
[2] Automatic Train Protection (such as ATB and ETCS)

2.1.3 Railway scheduling

In railway scheduling the most commonly used tool is a graphical representation of the timetable in a time-distance diagram. Here one can see the trains plotted in time and distance and are conflicts clearly visible. Depending on the level of detail one can see the acceleration of the train and block occupations for tight scheduling or one simply draws straight lines with separations according to planning standard. The latter is mostly used in developing the timetable whereupon the more detailed is used to see whether other conflicts in junctions and stations pop-up or not. A recent example of a time-distance diagram around Schiphol is given in figure 2.3.

The diagrams make different train types really recognizable by the angle of the line (speed) and their halting regime. Therefore one can see for example whether one can squeeze in an extra local train or not in-between two intercity trains. This all depends on the minimum needed headway of a train. The length of the line, the amount of stops, the difference between trains and the dwell times are all aspects playing a role in determining the headway. There are various types of headways to be distinguished which consists of relations like a "Departure-Departure" headway or similar with arriving, just like the planning standards. The difference in this case is that one often has to obey the end of a line to determine a headway at the beginning of the line. This is illustrated in (Hansen and Pachl, 2008) and shown in figure 2.4.

When high capacity is required, then the headways should be reduced to a minimum to avoid empty tracks. A way to achieve this is to increase homogeneity, which could for example mean that the amount of stops for intercity trains need to be increased and the speed and acceleration of local trains need to be improved. In this way the lines in the time-distance diagram will be more parallel, meaning less waste of capacity. Most metro systems have a hundred percent homogeneity and therefore a tremendously high capacity. A great example of this is the Moscow metro, with frequencies of up to 39 trains per hour, because of a 90 second interval (Sviridenkov, 2013). This is further elaborated on in section 2.2.3.

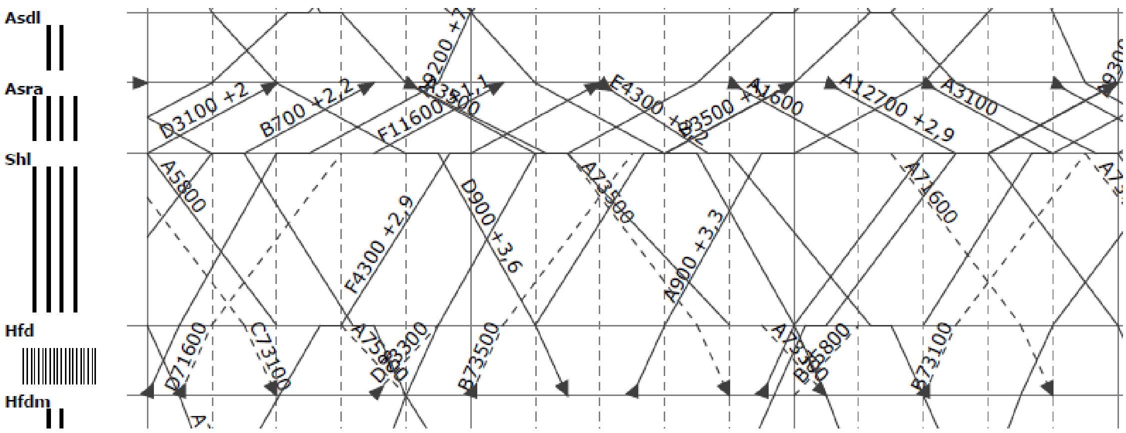


Figure 2.3: Time distance diagram of the Schiphol area with a 'width' of 30 minutes (ProRail).

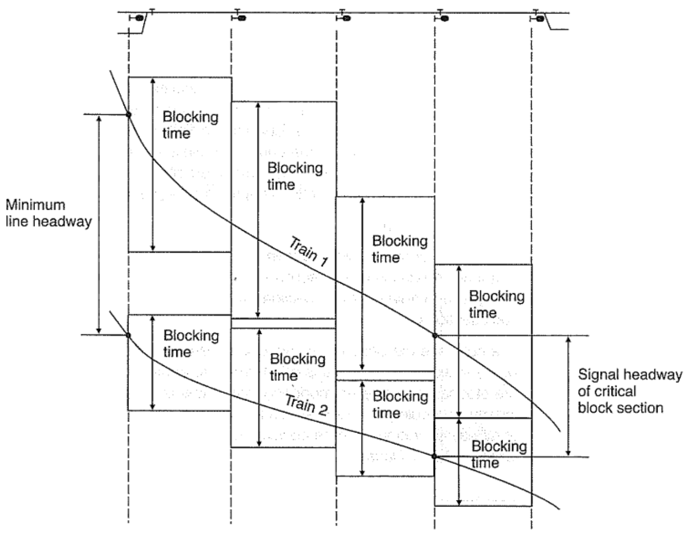


Figure 2.4: Minimum headways where train 2 is clearly a faster train (Hansen and Pachl, 2008).

2.2 Robustness of timetables

The effectiveness of a timetable is according to Hansen (2010) dependent on the following aspects:

- number of trains, passengers and load per time period;
- amount of passenger-kilometre and ton-kilometre per time period;
- operating and circulating speed of trains;
- headways and buffer times;
- scheduled waiting times;
- time and effort for modification and updating (rescheduling)

These strongly relate to the definition of capacity by the UIC earlier mentioned. Not only theoretic capacity aspects are taken into account, but also aspects for perturbed situations which are the last three. This actually means that the quality of operations is related to the quality of a timetable. In a good timetable measures are built in to keep the timetable stable, making sure that (small) disruptions will solve over time and will not get worse. This ability to handle minor delays is called robustness. There is however no exact definition of robustness, Goverde (2005) describes it as follows:

> A robust timetable must be able to deal with a certain amount of delay without traffic control intervention. Timetable robustness therefore determines the effectiveness of schedule adherence after disruptions.

The timetable must leave enough space to recover from disruptions which should lead to better punctuality. Initial delays must dissolve over time avoiding secondary delays in the operations. Different kind of delays are explained in section 2.4.2.

2.2.1 Buffer times and time supplements

The easiest way of assuring a robust timetable is implementing margins in the timetable. This can be done in various ways: a running time supplement can be added or some extra time can be added just before, after or at a station or junction or by adding buffer times between trains. The first are called running time supplements and are a measure of timetable slack (Hansen, 2004). A five percent surplus on the running time is commonly used and should cover smaller-scale delays like exceeding the dwell times or just a train driver driving slower than planned (UIC, 2004). This value is worked with by most railway companies around Europe. This method should not be overdone and handled with care. By adding too much running time supplements trains might arrive to early at stations and might encounter red signals. By having to halt just before the station, trains need more time to enter the station afterwards resulting in a suboptimal way of using the capacity.

Extra running time supplements are mostly seen just before the major railway station in the Netherlands. The reasons for this is twofold. First it assures that almost every train will at least depart the major stations on time. On time trains will be too early on stations having large dwell times, but this will cause minimum hindrance as on major stations most passengers will leave the train to either change trains or to arrive at their destination. This is a great way to increase punctuality, and is also seen for example in Switzerland. The punctuality directly leads us to the second reason why buffer times are just before the railway stations, which is a commercial reason. Punctuality is measured for the government at the major Dutch railway stations. As soon as trains are at these stations on time the punctuality grade of the railway operator rises (Hofs, 2011). Whether this is fair or not is disputable.

Buffer times are implemented extra times between train paths to have a margin between trains, to avoid interactions between them in case of minor delays. It can also be said that the minimum planned headways are on purpose kept longer. These buffer times are also part of the earlier mentioned planning standards in table 2.1

2.2.2 Capacity versus robustness

Applying buffer times make timetables more stable and robust, which is needed to comply with the last point of the UIC definition of capacity: "With market oriented quality". As especially the Dutch market demands punctual railway operations it can be said that robustness is part of capacity. But on the other hand the physical capacity is being decreased by buffer times. It simply means less trains can use the tracks (the first to part of the UIC definition). It seems that at busy lines a situation arises where capacity and robustness are becoming both opposites and part of each other.

A bottleneck like Schiphol railway station has to deal with dense railway traffic as well. In the development of today's DVM a lot of research by Schaafsma has been done to tackle the problem of capacity versus robustness (Schaafsma, 2006). He realised a buffer time in the station is dropping the capacity, and is therefore not an option as the station simply has to cope with the required amount of trains. A solution in the form of a surplus in running times is nevertheless not an option because this causes the tracks in the bottleneck to be occupied unnecessarily. The solution seems to be to accept dispunctuality locally and assure punctuality globally. To realize this the capacity in the bottleneck can be increased by eliminating buffer times. This causes a very non robust situation locally. To ensure a stable timetable the buffer times are implemented just after the bottleneck giving a train driver the chance again to drive on time. In this way capacity and robustness do not have to be opposites as long as it is observed on a larger scale.

2.2.3 Utilisation

Capacity remains a theoretical thing as long as it is not utilised. By determining the utilisation balance one can really say something about the capacity. This is dependent of the following four aspects: stability, average speed, speed differences (homogeneity) and amount of trains (UIC, 2004). Together these form a balance and a trade-off which are of importance for a DVM system around Schiphol. The conservative model chooses heterogeneity and average speed over the amount of trains and reliability. Today's market demands more trains with a reliable service, the corridor model, which means a shift in track utilisation (figure 2.5). Although the demand exists for a metro-like system, it needs to be combined with alternating services as well in combination with a multi-level train system to provide different service levels. At the station of Schiphol the homogeneity appears to be high at first sight as all trains do have to halt there. Looking closer in this issue the different driving characteristics of the trains and the differing dwell times cause a form of heterogeneity.

The effects of the four parameters of the utilisation balance are described in the following trade-offs below.

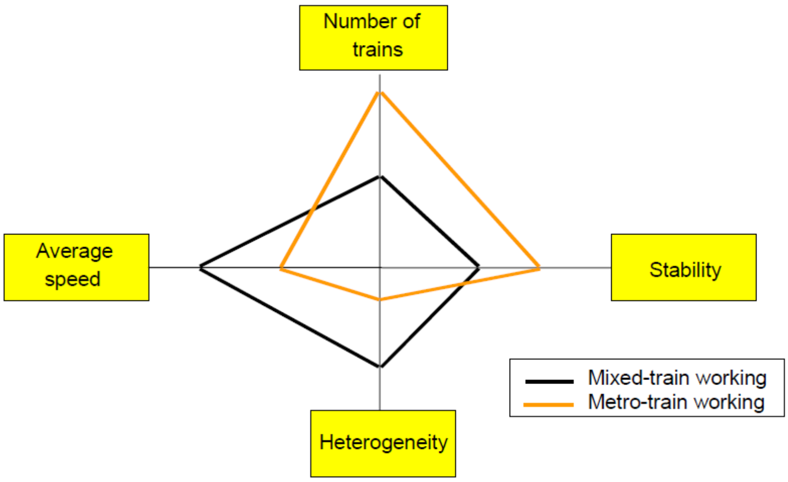


Figure 2.5: The utilisation balance. The heterogeneous model in black, the corridor or metro model in orange (Schaafsma, 2001; UIC, 2004).

Homogeneity versus heterogeneity

Heterogeneity can be considered the most capacity consuming aspect in the utilisation of railways. It is caused by variations in speed and stop patterns and by variations in headway times caused by stochastic effects (Landex, 2008). Normally this is mainly an issue on double-track railways. A single-track's capacity is already limited by it's crossing possibilities and quadruple-tracks mostly have a train-speed based allocation of trains. At the four-track Schiphol tunnel this is not the case because the trains run mixed as the allocation of trains is mostly determined by their destination (westbound) or origin (eastbound) and not the train it's characteristics. Homogenization en route can be accomplished in multiple ways (Vromans et al., 2006). First one can compromise the train speeds of different train types by slowing down long distance trains and speed up local trains by using better rolling stock or decrease their running time supplements. A similar thing can be done by compromising the halting regimes of the trains: express trains could halt more often at stations. Furthermore overtaking is an option to increase homogeneity. This however increases dependencies between train services and therefore decrease stability of a timetable. Lastly shorter train lines also have benefits for homogenization. In figure 2.7 the capacity consumption of both a homogeneous and heterogeneous timetable is illustrated. It is clearly visible that homogeneous timetables are able to handle far more trains. This was also shortly mentioned in section 2.1.3.

Stability versus amount of trains

By increasing frequencies one loses time on buffers which are needed for recovery from perturbed situations. A train schedule can theoretically have as many trains per hour as the minimum headway would allow. In case of this unlikely example a delay of a train will propagate directly to every following train. This effect decreases by implementing buffers between trains which does however decreases the maximum amount of trains. Reliability is for a large part responsible for the capacity which is to a large extent dependent of the capability of recovery, or simply stability. Passengers might encounter negative effects of instability directly. In a metro-like system, delay propagation is a smaller problem as the next train offers the exact same service. In heavy-rail the contrary is true. Including buffer-times enlarges the scheduled headways but returns more stable railway operations. What larger headways have for consequences for the physical capacity is visible in figure 2.8.

Average speed

The speed of a train is of great influence on their competitiveness with other modes of transport due to the underlying travel times. Higher speed does not necessarily mean a higher capacity on the network, there is an optimum for the maximum speed based on many aspects. At higher speeds the minimum headway is mainly depended on the block length and the train speed. At lower speeds also other parameters like the train length become more significant. In case one uses ERTMS level 2 the optimal headways are illustrated in figure 2.6. In the Netherlands the typical block length is between 1200 en 2000 meters and still ATB is used as train protection. For ATB shape of the graph will be roughly the same with different values. Around the Schiphol tunnel the blocks are shorter to optimize headways for the lower speeds. Speed effects become larger if one includes the halting regime in the average speed. The stops cause headways to significantly enlarge and decrease capacity.

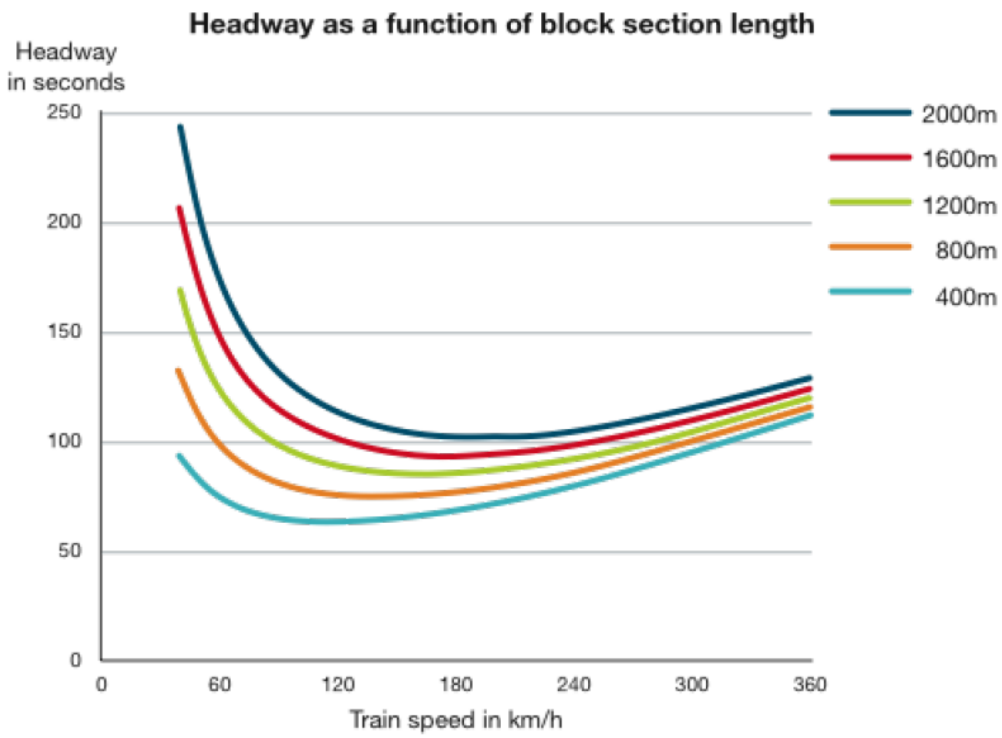


Figure 2.6: The minimum headway as function of the maximum speed and the block length using ERTMS level 2 (Hunyadi, 2011).

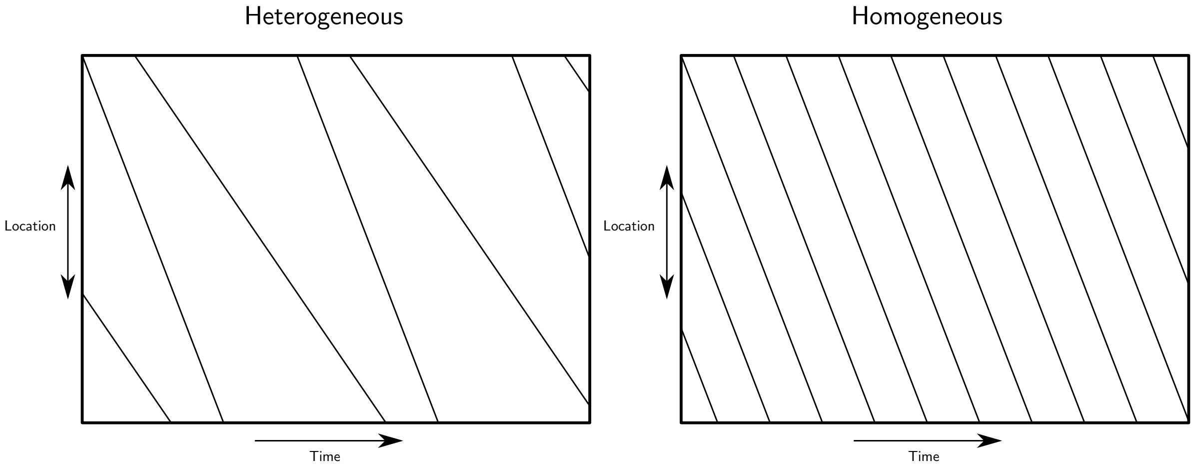


Figure 2.7: Left a heterogeneous utilisation of a track as seen in a classical two train (local and express) service pattern. On the right a homogeneous utilisation of a track which results in a much higher amount of trains per hour but will not satisfy all the customers their demands.

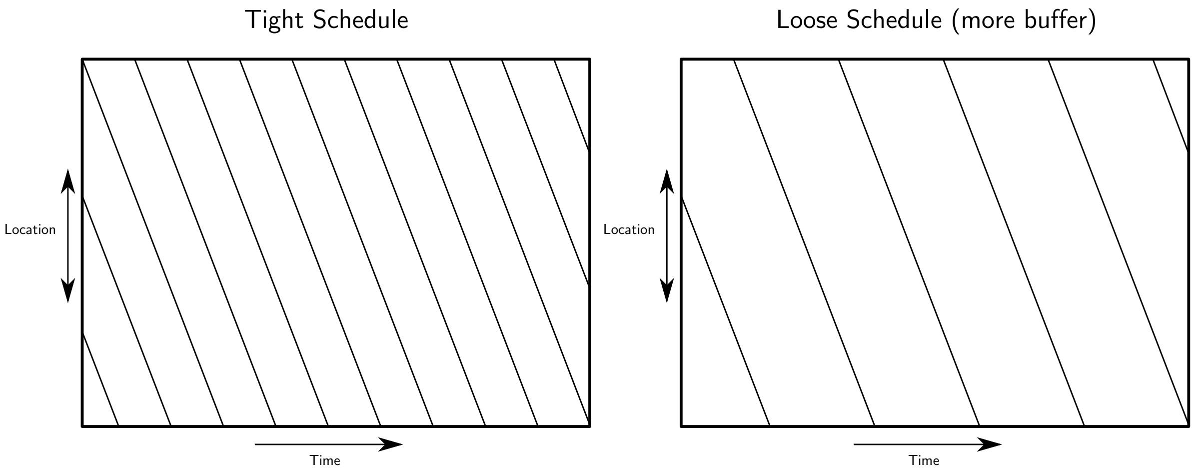


Figure 2.8: Left a tight schedule with limited buffer times included, which is less stable during disruptions. On the right a more 'loose' schedule with lots of buffer times, which are very usable for recovery of disrupted situations.

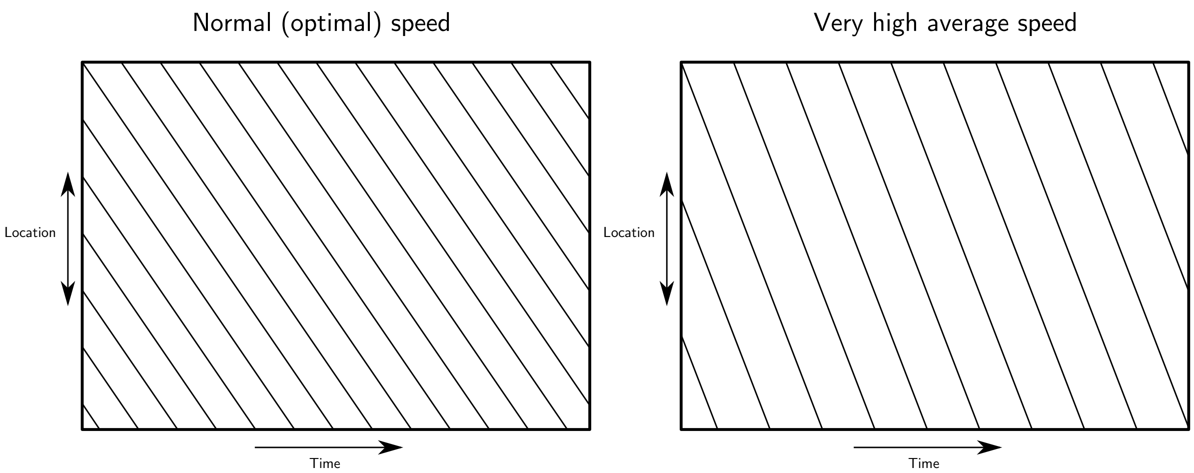


Figure 2.9: Left a low speed train service with relatively small buffers needed for a stable service. On the right a high speed train service where relatively large buffers are needed for a stable service.

2.3 Dynamic railway traffic management

The DVM system in Schiphol approaches planning in a whole different way. Instead of fixed plans with buffers the Schiphol area functions as a black box where only entrance and exit times are really planned. Within the box the paths are rather flexible. Both in normal as in perturbed situations the system deals with trains in the same way.

2.3.1 Flexible scheduling within bottlenecks

The black box principle pushes trains through the bottleneck as fast as possible, with no extra margins in dwell or running times. Because of this trains are actually always late at the station of Schiphol airport. By having the buffer after the bottleneck, the train can run perfectly on time again afterwards. A major disadvantage of this principle is the uncertainty within the bottleneck. Since trains are being dealt with as fast as possible one needs to communicate to the passengers the earliest possible departure time which won't be accurate in most cases. For the arrival time however counts the opposite: the latest possible 'normal' arrival time should be in the timetables. This could even result in trains arriving later at stations in bottlenecks than they depart. For train drivers only the earliest allowed departure times are interesting to know. This differs from the passenger timetable and is called the working timetable which is mostly much more accurate as it does not use minutes as smallest unit but seconds.

To operate the flexible timetable normal instruments of the signallers are insufficient. Assistance of the dynamic traffic management system is needed as the signallers can't hold any longer to a fixed timetable, as this became flexible. The timely flexibility also comes with a new merging regime at the junctions, for example Asra. Where normally the order of the trains are mostly maintained, the system just lets the first train go first (FCFS). To decide which train came first a threshold point of at least two blocks in advance is needed. The order of entering the tunnel will also be the order of leaving the tunnel resulting in the first in first out principle (FIFO). In the case of Schiphol there is one exception in the direction of the 'Zuid-as'. Here delayed local trains might not go before an intercity if the margin between the trains is less than 100 seconds. With these simple rules two tasks of the signallers are eliminated already and the capacity is improved.

The time wise flexibility is a solid start for a high capacity at the bottleneck. To make railway operations even more effective also a certain flexibility in routing is needed as well. As earlier reported. Normally according to the planning standard two trains can follow each other up every three minutes. Due to optimal signal placement this already reduced to two minutes in the Schiphol tunnel (van Leeuwen, 2013). The required interval between halting trains at a station is about four minutes. To optimise the use of the tunnel the Cross-Platform switch (XPS) was introduced. One platform will be used on both sides handling trains all coming from one and the same track. Passengers only know a couple minutes in advance on which side they can expect their train. Also this is done fully automatic by the DVM alternating trains between platform sides (Schaafsma, 2006). Saliently is however that this flexible planning roars against al planning standard which should ensure the first layer of safety.

2.3.2 Examples

Some (other) examples of flexible scheduling are described in this section. The case of Schiphol is a very good example, but has already been elaborated on in section 1.3 and just above this one at section 2.3.1.

A case of first come first served can be found near the village of Liempde in Brabant (Weeda and Hofstra, 2008). Here every 30 minutes two intercity lines in south-eastern direction have to cross each other, contrary to the other direction, at level. These two trains are scheduled more or less at the same time. No order is planned for the crossing as this could mean unnecessary waiting by one of them if the other has a minor delay. Due to stochastic reasons the chance of the two trains arriving at the same time is very low. The case is illustrated in figure 2.10.

In the Zürich S-Bahn an example of the Cross-Platform switch can be found. The network of commuter trains in the largest city of Switzerland is a very busy one. Like at Schiphol one of the stations at Zürich main railway station is underground. It consists of a double track tunnel with a quadruple track station. Per direction one track is available and a single platform with two side. A

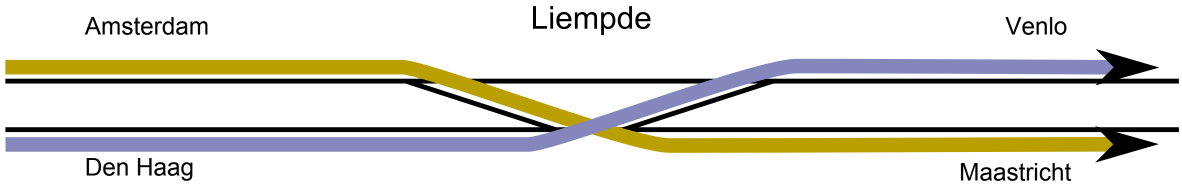
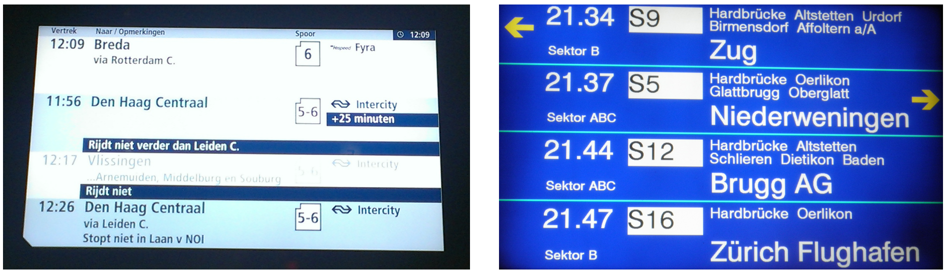


Figure 2.10: The crossing of two intercity trains in Liempde based on the FCFS regime.

little DVM system decides on which platform the train might enter the station. Contrary to Schiphol this does not happen exclusively alternating, however this is often the case. This particular system let trains enter the inner platform track if available, else it will choose the outer one. In peak hours this results in an alternating usage of platform sides. Although this is an example of flexible routing it is not an example of timely flexible planning because there is actually buffer time available in the dwell times at Zürich main station. The design of the passenger information used to be very similar to the one at Schiphol.



(a) Schiphol (b) Zürich HB

Figure 2.11: Platform information in different styles. The platform side is published on the screen just before arrival of the train.

2.4 Railway monitoring

Before railway performance can be determined data collection is necessary. In the Netherlands trains are being monitored continuously in several ways. How the data is being gathered is explained in the following section.

2.4.1 Railway operation monitoring

Trains carry a unique number, both physically and for their course in the schedule. With these numbers, especially the second one, trains can be followed over the network. An automated system, TROTS[3] , logs all movements of a train, which can be done as accurate as the amount of present infra elements. Infra elements consist of track sections, switches, signals and more. In the future frequent positioning of Euro-balises, train-position messages from the train or even virtual GPS-Balises (GNSS-2) might even improve the accuracy of the tracking as part of the European Rail Traffic Management System (ERTMS). The log files of TROTS are carefully stored and partially automatically analysed to determine for example the daily punctuality rate, which is published every working day. For more detailed information about for example corridors, train series and accidents the log files can be read out manually. As soon as a train has a delay of more than three minutes, the signaller must give a reason for this delay. The information is a valuable add-on to the data TROTS is gathering.

To find structural problems in the railway operations it makes sense to analyse a single train series. With a large enough dataset (for example a whole month) one can find out where operations are regularly disturbed. A very valuable tool for this is the bandwidth graph which makes recognizing problems easy. In these graphs it is easy to see whether delays are caused by too tight scheduling or

[3]TRain Observation and Tracking System

by other factors. These graphs are produced by TRENTO[4] , which is a piece of software specifically made to read the data from TROTS. An example of such a graph is showed in figure 2.12. Vertically the graph shows the delay in seconds, horizontally the route. The lines within the graph represent every 10th percentile. The red one is the median which is a useful benchmark. If the lines converge, it means trains are able to recover from (minor) delays. Are the lines parallel, but heading upwards it means the timetable does not allows enough time for the particular part of the route. This is more of a scheduling issue and not very problematic. The worrisome parts of the graph are those diverging. These are locations where structurally delays are present.

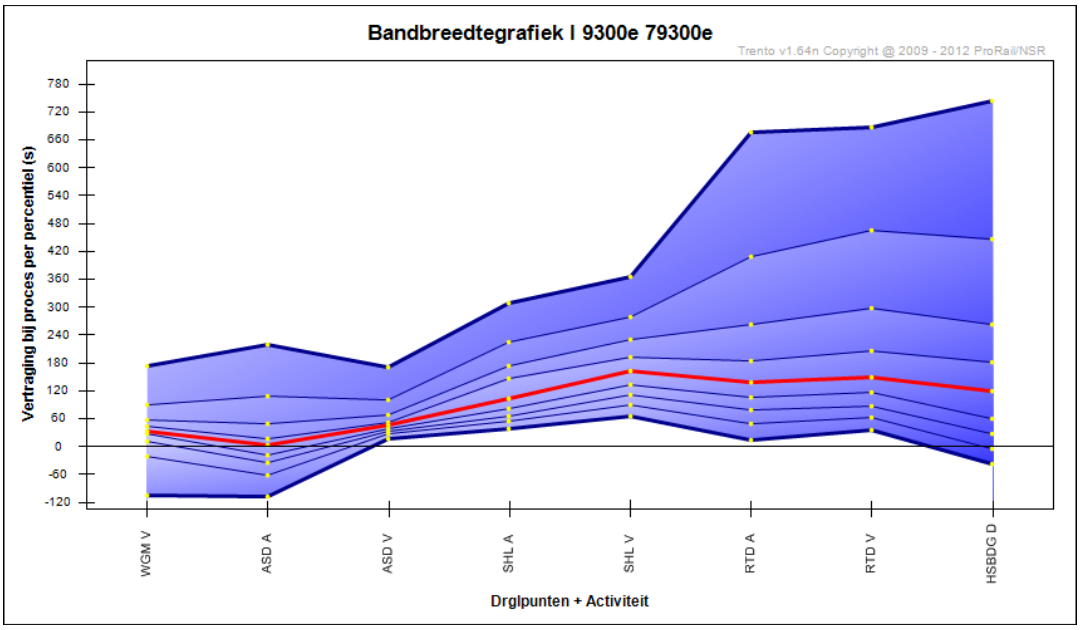


Figure 2.12: Bandwith graph of the Paris-bound Thalys (ProRail/NSR).

As soon as locations and times are known where regularly delays occur one can do a more precise analysis of the problem. This is normally done by the Performance Analysis Department of ProRail (PAB). For the particular case of Schiphol analysis has been performed by order of NS Hispeed (PAB-ProRail, 2012). The results show some of the problems around Schiphol. Mostly the schedule seems to be causing some trains to hinder others, which is a signal of not enough buffer between trains. This results in different orders of trains which is of course partially to be blamed on the FCFS algorithm. However this could be seen as the idea behind the DVM system. It sometimes results in unwanted delays.

2.4.2 Delays

While analyzing individual cases in railway operations one has to make clear distinctions between two kind of delays: the initial, and the secondary (knock-on) delay. Literature (Hansen and Pachl, 2008) gives the following definitions of these:

> *Initial delay: A delay recorded at the cordon of an investigated network when the trains enters that network.*

> *Knock-on: A delay caused by other trains due to either short headway times or late transfer connections.*

Why is it so important to know the difference between the delays? As soon as the performance of a part of the railway network has to be analyzed one has to cope with trains entering that part of the network with a delay. This train's delay is not to be blamed by the performance of the analyzed

[4] TRots & TOol

stretch. The amount of secondary delays this train might cause is however to be influenced with the way of controlling an area. The amount of secondary delays is therefore a good way to measure the performance of for example a DVM system. A descend controlling algorithm should be able to minimize secondary delays, even let initial delays (partially) recover and maintain a high throughput. This means it is the goal to let trains pass the Schiphol Tunnel as unhindered as possible without any (extra) waiting times. To have a good insight in how the delays recover, one should both test in perturbed as in unperturbed situations.

2.5 Incidents and minor disruptions

Disruptions are unavoidable in daily railway operations. To have a reliable service both the infrastructure as the schedule should offer space for recovery. One can determine two different kind of disruptions: incidents and minor disruptions. They are dealt with differently as will be elaborated on in this section.

2.5.1 Disruptions

Disruptions are causing perturbed traffic states on the tracks. In general these are solved by signallers based on simple rules pre-defined in documents. These train dispatching documents (TAD'en[5]) tell what to do with certain delayed trains and when to re-order them. Indirectly it says something about the priorities of trains, mostly based on hindrance of a delayed train further en route. For example, as soon as a local train in front of an express train is delayed more than x minutes, the TAD might state to arrange an overtaking at a certain place. This level of train controlling is exactly the level of where a DVM system is functioning and therefore it is useful to analyse how trains are handled here. More on the TAD'en in section 3.3.1.

2.5.2 Incidents

Incidents are in fact major disruptions in the railway operations which can not easily be solved by trying to continue the regular train service. Incidents can be broken trains on the tracks, switches malfunctioning or a tunnel's fire alarm going off[6]. A DVM system is not capable of handling major problems as it is not intended to be able to make decisions about whether trains should be cancelled or not. The complexity of incidents cause traffic controllers to rely on pre-made scenario's, the so-called VSM's or obstruction measures. These describe which train services need to be cancelled or changed. In today's situation in case of an accident the DVM will be turned of to be able to adjust train paths manually and facilitate turning movements. With the future DVM system it is assumed to be the same.

[5]Trein Afhandelings Documenten in Dutch

[6]Which is unfortunately a common incident in the Schiphol tunnel

2.6 Developments in dynamic railway traffic management

In this section alternatives of the DVM system will be described and compared. This will show both negative and positive aspects of the system. First the mode of operation will be taken into account, followed by a section about optimization and forecasting which will elaborate on new developments. Combining these two aspects one comes to the DVM alternatives. This is mainly focussed on real-time rescheduling as this is the most tricky part during operations. The options are illustrated in the next table and the development relations in figure 2.13. Forecasting focusses more on incidents where automation is more used to handle (disrupted) high-frequency railway operations.

Table 2.2: Overview of alternatives to DVM.

Mode of operation	Without real-time forecasting	With real-time forecasting
Manually (signaller)	Conventional train dispatching	Swiss system RCS (only conflict forecasting)
Automatically	DVM	Future - ROMA

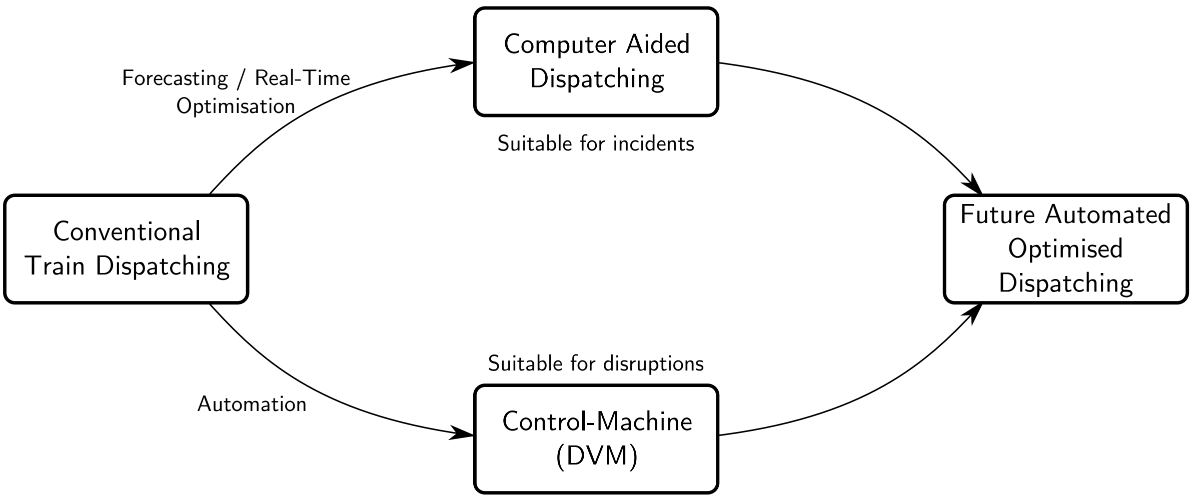


Figure 2.13: Developments in train dispatching.

2.6.1 Modes of operation

Basically there are two ways of dispatching trains: either manually or automatically. The manual way is the conventional way as it's done nowadays at most places, and has been done this way ever since. By doing so, one has both the advantages and the restrictions of the human capabilities. A signaller can make great decision optimizing the train system based on rules and his experience. On the other hand, there is a great chance that a signaller makes sub-optimal decisions, especially during stressful periods with perturbed operations: the moments when the signaller is needed the most. Under normal circumstances the dispatchers can relax and observe what is happening. Automation has set in into dispatching as 'ARI' already automatically handles the on-time trains with a five minute margin. Only as soon as reordering is needed, the dispatcher must interfere. The amount of trains that can be rescheduled per hour is limited by human capacity.

Automated modes of operation are nowadays found in dynamic traffic management systems. They consist of simple rules to avoid safety problems. The main advantages consist of making no mistakes and saving money by reducing signallers. However during major disruptions these systems should be controllable and understandable. Signallers need to know why the system makes a certain decision. As long as automated systems are simple, this can be realised.

2.6.2 Real-time optimisation and forecasting

Signallers nowadays receive real-time information about the locations of the trains in the network. With this information and their experience the traffic controllers are doing their work as good as they can. In perturbed situations they virtually have to look in the future to find the optimal paths for their trains avoiding conflicts. In a complex and crowded network, as the Dutch system is, this could lead to difficulties for the signallers. Forecasting is the solution to real-time detect future conflicts. The Swiss already use this to assist their signallers (Völcker, 2010). By going even one step further one could use this forecast to optimize future train operations. This is currently developed to inform signallers about the best options for rescheduling (Corman, 2010). If these solutions could be used by automated traffic control systems it could mean that even during disruptions problems will be minor and delays might dissolve faster than currently without any human interferences. As calculating optima is nowadays still a time consuming process it might take a while before these forms of signalling are introduced. The practical problem arising with this development is that it is desirable that a signaller should be able to understand all the decisions. Unless the desire for simple controlling systems is put aside this kind of controlling won't be implemented any-time soon.

2.7 Summary and conclusion

Railway capacity doesn't only consist of the physical availability of the railway tracks according the UIC code 406. Also the 'market-oriented quality' is part of the of the capacity, requiring that the use of the tracks occur in a robust manner. Formulated differently it means that one has to find a balance between number of trains, stability, heterogeneity and average speed. It is impossible to have excellent performance on all of those four aspects. Stability is a keyword in the performance of railways because the customers experience the most of it. To acquire stability it is common to implement buffers in the timetables, both between trains and in running times of individual trains (running time supplement). In case of a bottleneck one tries to squeeze as much trains as possible through this point. This is hard to combine with buffers. At Schiphol they decided to allow small instabilities (in arrival and departure times) to ensure an high throughput. The possible delays received in the Schiphol tunnel are absorbed by buffers after the bottleneck. To cope with disruptions and incidents, rescheduling is necessary. Generally this is done by train dispatchers, but in the last decade new developments are changing this. In case of incidents the dispatcher can be assisted by computers, which are able to predict future conflicts. In case of disruptions, control-machines (DVM) can handle trains flexibly by pre-determined rules. A combinations of the two could lead - in the future - to the ultimate dispatching system.

Chapter 3

Requirements and possibilities for a new system

3.1 Stakeholders

In this research five main stakeholders can be determined. These are the government(s), ProRail, NS Hispeed, NS Reizigers and the passengers. However they mainly share the same vision, there are some tensions and different interests. This chapter tries to give a clear overview of them and their wishes and requirements for a DVM. Before elaborating on their interest first a brief overview of their relations.

3.1.1 Relations

In figure 3.1 the relations between stakeholders are visualised.

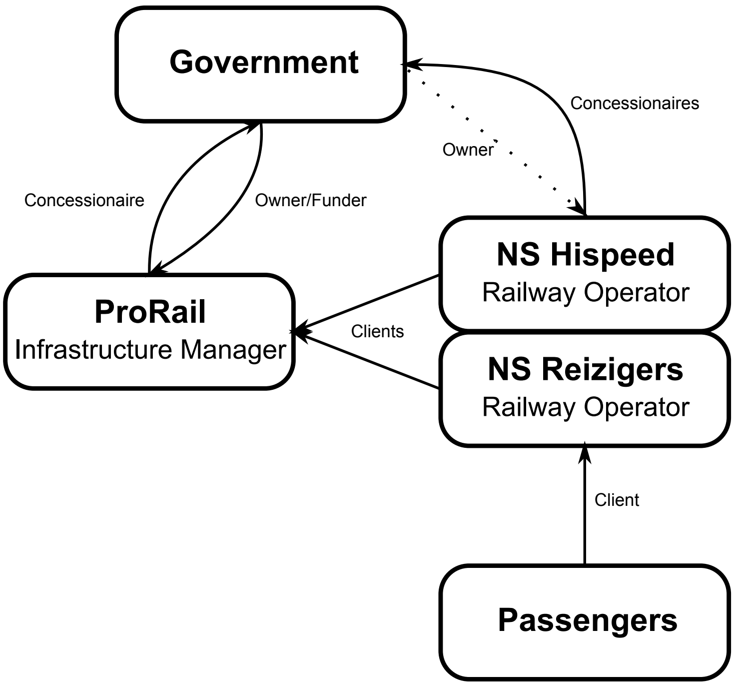


Figure 3.1: Relations between stakeholders.

3.1.2 Stakeholder characteristics

The government periodically publishes their vision about the railway system of the country. They try to act on behalf of the passengers. Being the (largest) funder of infrastructure project they have a veto about practically everything. They fully own ProRail however it is a private company (LTD). The same holds for the Dutch National Railways where they even are a public limited company (PLC). Their main goal is to improve the quality of the railways as a mean of transport to increase the attractiveness for both passengers and railway operators (Rijksoverheid, 2013). Ambitions of the government consist of increasing the service by means of reliability, travel times, comfort, accessibility and (real-time) travel information. They want to this on basis of three main points: quality, capacity, attractiveness. The government budgets about two to three billion euro's for railways yearly. This budget is mostly invested in infrastructure via ProRail. A new DVM system at Schiphol is seen as part of the SAAL corridor by the government.

ProRail is the national infrastructure manager (fully owned by the government) and is therefore responsible for maintenance, safety and construction of new tracks. They have to divide railway capacity in a fair way without giving monopolies to operators. ProRail operates the actual DVM system and is also developing solutions for the near future as they are seeing problems as well. Their main requirements is a transparent, predictable and controllable system. This means that signallers do understand the decisions of the system and can take over the system in case of large disruptions, like a (false) fire alarm in the tunnel. This requires the system to be rather simple. Furthermore a new DVM should be able to guarantee enough throughput with respect to safety and robustness.

The Dutch National Railways (NS) is a commercial, internationally operating holding, fully owned by the government. Their biggest and most known railway operating company is NS Reizigers (travellers). They own today's concession of the main rail network (HRN[1]) and therefore operate practically all inland intercity services and a big amount of local services. As being the Netherland's biggest railway operator they are planning the most of the schedule of the country in (mostly) good cooperation with ProRail. For them a well functioning DVM is very important, as delays will cause their customers to be unsatisfied with their service. As being the national railways they have to guarantee a certain level of service as is stated by the government. This is based on the quality of operations, which consists of for example punctuality and the grades given by passengers. In the future NS will get a concession of both the HRN as the High Speed Line (HSL) causing an integration of both networks. This changes the routing of the intercity and high-speed lines significantly. More important, it causes new transfer relations to be created which is problematic for today's throughput at Schiphol. NS plans on offering a Cross-Platform Transfer for their passengers on Schiphol which today's system is not capable of. Later in this chapter the Cross-Platform transfer is elaborated on further.

[1]HoofdRailNet

Part of the NS holding is also railway operator NS Hispeed. This is their high-speed division consisting of both national and international trains. Their main focus is on the so-called PBKALF cities: Paris, Brussels, Cologne, Amsterdam, London and Frankfurt. Being partners with neighbouring railway companies they are able to provide their customers trips to these cities and in-between. The national service between Amsterdam via Rotterdam to Breda is fully operated by themselves. NS Hispeed operates at speeds up to 300 km/h and competes therefore strongly with car and airplane. Their national and their international Belgium and France-bound trains also pass bottleneck Schiphol. International trains and passengers have some different characteristics compared to the national trains. NS Hispeed feels that the lack of differentiation of trains by today's DVM causes sub-optimal use of Schiphol's capacity harming the quality of operations of both railway operators. This is regularly seen at Schiphol by local trains having to wait for the long dwell time of a high-speed train, or the other way around at the Asra junction because of the FCFS algorithm. Due to future developments NS Hispeed's wishes and requirements are equal as those of NSR as they will operate together.

Passengers

There are several types of passengers at Schiphol airport all having different reasons for using it. They vary from tourists to daily commuters and from transferring passengers to the ones catching a plane at Schiphol. Research by the NS is showing the main demands of the passengers during their trip. They consist of : safety & reliability (50%), speed (15%), ease (14%), comfort (12%), perception (9%) (NS, 2012b). It is no surprise all previously mentioned stakeholders require reliability as the end-user, the passenger, is demanding it as well. When developing a new DVM it is important to know the characteristics of the different passengers. A daily commuter might not have problems with short transfer as an incidental passenger might need some extra time. The end-user should never be forgotten in designing new things in general.

3.1.3 Conflicts

All stakeholders share most points of their vision about railway traffic in the Netherlands: delivering an attractive and reliable product to the end-user. When it comes to controlling traffic and the earlier mentioned definition of capacity, there is a conflict arising. In this field one could say that NS and ProRail are having a different vision. But also the government, and with that, politics play a role. NS is a commercial company striving to deliver a product conforming the market by offering high frequencies and preferably direct connections for their customers. By servicing the passengers[2] by their demands, they deliver ProRail a 'spaghetti' of lines. By doing so, more crossing movements arise than for example in a corridor oriented service pattern. ProRail tries to use capacity on the tracks as efficient as possible to serve as many operators (customers) as they can in a reliable way. These two goals conflict sometimes. Referring to the UIC code 406, one could state that both parties, NS and ProRail, want to optimally use capacity according to the three points. The friction however arises at the third point : "with market-oriented quality". The markets are totally different: ProRail servers operators and NS servers passengers. With these different interests it is sometimes hard to come to an optimal solution for both.

For a DVM system this holds as well. Also at the Schiphol area NS wants to serve their customers as good as possible by offering a wide range of destinations and the later mentioned cross-platform transfer. NS knows their schedule demands an complex controlling system. ProRail however want to keep such a system controllable, simple and understandable which is from their point of view obvious

[2]and partially politics

as it has been that way forever. If automation sets in a signaller still wants to understand the decisions a machine makes. One could assume this results in not being able to offer an optimal controlling regime which NS might suffer by. A future DVM system should satisfy both parties as much as possible.

3.1.4 Combined requirements and wishes

By looking at the five main stakeholders a list of requirements and wishes can be formulated. These should give guidance while developing an automated system.

Requirements:

- The new system should be a **safe** system
- Capable of handling the future **timetable** stably, also during perturbations (including XPT)
- Fully **automated**
- **controllable** or switchable (able to turn off in case of incident)

Wishes:

- **Passengers should know** their platform well in advance[3]
- The concept is preferably **simple** and therefore **understandable**

3.2 The future and its challenges

The future will bring several changes to the Dutch railways especially in the SAAL corridor (Schiphol, Amsterdam, Almere, Lelystad. The timetable will adapt to higher demands and therefore infrastructure will be expanded. In order to provide high quality railway transport, with good attractiveness for the public, frequencies will go up to a metro-like system.

3.2.1 infrastructural changes

As already introduced in section 1.2.2 the Amsterdam Riekerpolder Aansluiting will change significantly over time (visualised in figure 3.2). Also the Zuid-as will be expanded to quadruple tracks as part of the OV-SAAL project (ProRail, 2013b). In this way high frequency train services can be provided between both Almere and Schiphol and Utrecht and Schiphol. The quadruple track on the Zuid-as however will not be facilitating switching between the inner and outer track. Coming from the eastside the decision for the track use in the tunnel has to be made already at Duivendrecht Aansluiting West (DVAW). This is due to the fact that the amount of switches in the Netherlands should be lowered to make the network less vulnerable for interruptions. This is partially based on the Japanese example where they strive to use very low amount of switches as well on their lines. A bit of flexibility is sacrificed in exchange for robustness in the operations. This change means a new DVM system needs to adapt to this and already take into account the DVAW junction.

Besides the expanded junctions and the increased amount of infrastructure, some switches in the Schiphol tunnel will be removed. These are switches not being used within the schedule but only needed for real-time rescheduling. Those switches are nowadays minimized to reduce disruptions due to breakdowns. Only at 'decoupling-points' on a corridor, these switches are present. It is part of ProRail's vision on robustness nowadays (Schaafsma, 2012). This results in reduced possibilities for routing within the tunnel of Schiphol.

[3] The platform-**side** however can be changed up to 5 minutes before arrival of the train

Figure 3.2: Amsterdam Riekerpolder aansluiting: the 2018 lay-out (Movares).

3.2.2 Integration HSL - HRN

Starting from 2015 the main rail network and the high-speed line are merged into one concession. This has major influences on both the intercity and high-speed network. It means that starting from 2015 high-speed trains might run over conventional parts of the network, the conventional trains could run via the high-speed line or both might be a good solution. Research shows that the integration of (semi)high speed trains in the network is the best solution of the three options (Zijdemans, 2012). This results in some major changes. First of all this does not correspond to the original PHS[4] plans which were the long term plans for the Dutch rail network in 2020. These plans, based on high frequency corridors in the network, are partially outdated anyways, since frequencies are already higher at some areas as stated in the 2020 plans.

By integrating the high speed line into the conventional network, Schiphol will become an ever bigger pivot in the network. The new concession gives the possibility to let high speed trains coming from the south continue in the direction of Almere and even further to the northern provinces. However this leads to great benefits for the ridership on the rail network and accessibility of these regions in the northeast, it also has major influences on the routing of the trains around the station of Schiphol. NS plans on driving the high-speed trains alternating between the HSL and Amsterdam and the HSL and Almere. This results in the national high-speed trains calling four times per direction at Schiphol Airport. To offer passengers a more frequent connection to and from both the Amsterdam and Almere branch, Cross-Platform transfers will be offered. This results in direct connections between all branches, with high frequencies.

An overview of all the intercity and high speed trains calling at Schiphol is shown in figure 3.3 and consists of twelve intercity and five Fyra high-speed trains (now: "Intercity direct") per hour per direction.

3.2.3 Cross-Platform Transfer

The Cross-Platform transferring has some problems combined with an DVM system. This is because of several aspects which are being found in the basic principles of today's system. First of all the main goal was to squeeze trains through the bottleneck as fast as possible and give them their buffer times just after it. By creating a transfer relation between two trains it means two trains have to wait for each other which is about the opposite of the mentioned principle. In today's praxis it is found one needs about three to four minutes dwell time of both trains for a smooth Cross-Platform Transfer. Another

[4]Programma Hoogfrequent Spoor

Figure 3.3: The possible IC/HSR network by 2018 (Roel Zijdemans).

version where one train halts long and one short, could also be a solution for a XPT. The transferring requires extra time to be scheduled in the tunnel but at perturbed situation things are actually getting really complicated as one has to state limits on waiting times and more. The second problem arising is the Cross-Platform Switch which cannot be carried out any-more when a XPT is necessary. This is due to the fact that both platform sides are needed for the transferring, the only dynamic thing one could do would be switching the two trains, but whether that would be an advantage or not is questionable. This means that four times an hour, for several minutes when the transfer is taking place, a XPS is not possible. Also today's keeping your lane function of DVM conflicts with at XPT as trains have to go from the inner tracks to the outer platform. The required routing for two westbound trains is shown in figure 3.4.

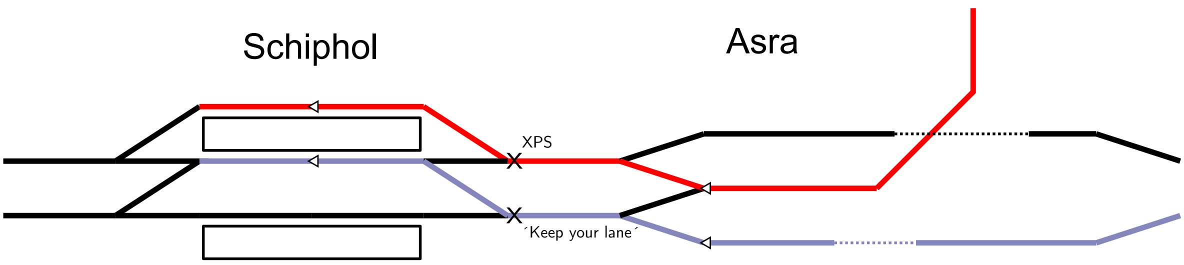


Figure 3.4: Two westbound trains entering the Schiphol train station simultaneously. The crosses mark the conflicting points with today's DVM.

The conflicts with today's dynamic system and the future schedule already show that the system needs an upgrade. The simple dynamic aspects cannot be combined with the increased complexity and demands of the railway operator. The main concern is whether the requested schedule can be carried out through such a bottleneck. A new, more sophisticated, system could solve this issue. It should be capable of handling train (series) specific rules, to for example make a difference between XPT- and non-XPT-trains.

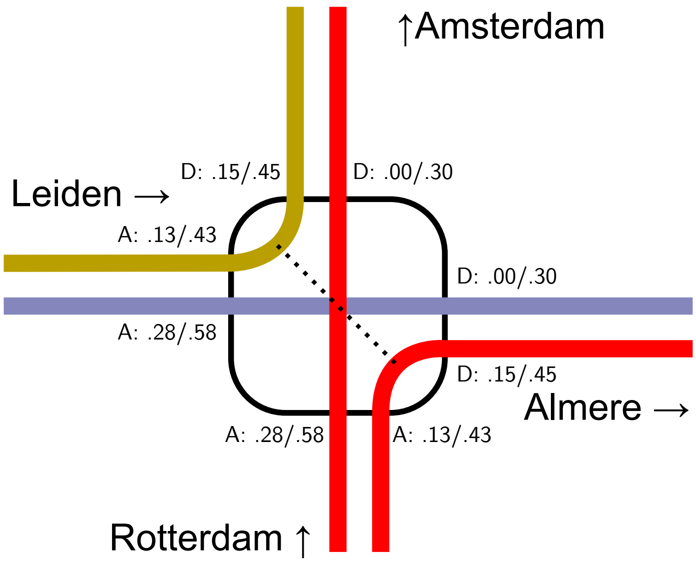


Figure 3.5: Concept of the alternating IC/HST services at Schiphol with a frquency of two times per hour per line. The dotted line shows the transfer relations. The times are only indications, a shift in time in the schedule is always possible.

3.3 Traffic control tools

Before actually determining how automated control and rescheduling can be configured, first both the Dutch and Swiss examples of railway traffic control are briefly explained. Later on the different aspects of rescheduling are considered as building blocks for a new system.

3.3.1 Examples

The following two examples will illustrate how train control has a role in rescheduling.

The Netherlands

In the Netherlands all trains are scheduled by using process lines which are short rules which sets routes automatically for specific trains on a specific time as long as the train is on time within a margin of about five minutes. These lines form the route process plan and are the basis for ARI, the automated route-setting machine of the Dutch railway system. As soon as trains are delayed, the signaller has to acknowledge this and decide if the order of the trains remains the same or if a reordering is necessary. For a lot of situations there are documents available to assist the signaller with his decisions the earlier mentioned TAD'en, which are basically a short series if/else statements describing the priorities between trains. If there is no rule for a certain train or combination of them, the signaller might handle based on experience (ProRail, 2010). The information needed comes from TROTS[5]. This follower of the former train number following system (TNV) is able to see what track elements a certain train is occupying. Figure 3.6 shows full overview of the control loop of train operations in the Netherlands.

Switzerland

The Swiss railway system has many similarities with the Dutch. The two countries learn a lot from each other as they both have a complex and busy system. A difference occurs in the control loops. Here the Swiss have added one extra step of rescheduling. They use real-time forecasting for conflict detection which is very useful in case of perturbed railway operations. In that way the signallers do not have to handle subjectively in rescheduling but are assisted by computer calculations making smarter decisions in optimizing railway operations. This system is most useful for larger delays as the minor

[5]TRain Observation and Tracking System

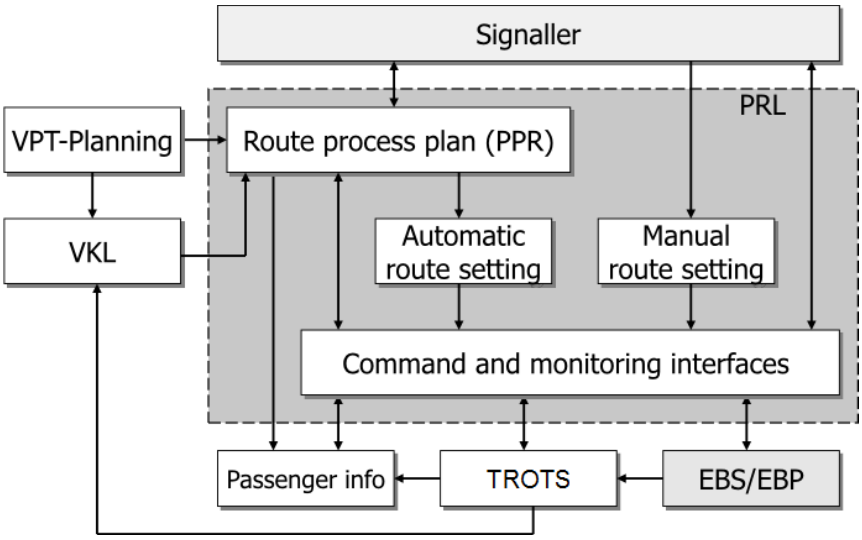


Figure 3.6: Dutch controlling strategy (Goverde, 2012).

delays (<5 min.) mostly should dissolve over time anyway. But even in those situations it can optimise the smaller decisions, which in the end can have great impacts. The Swiss control loop(s) are illustrated in figure 3.7.

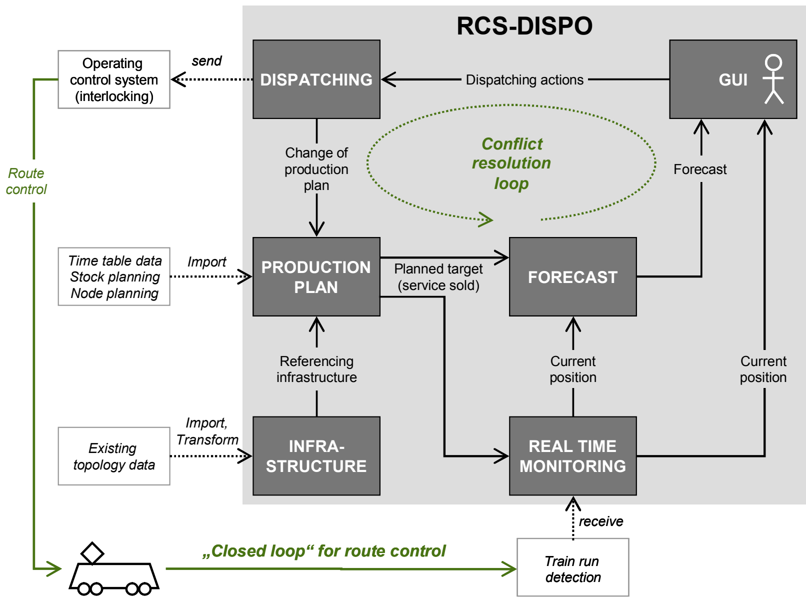


Figure 3.7: Swiss controlling strategy with conflict resolution (Krista, 2009).

3.3.2 Rescheduling and its components

In case of disruptions on the tracks rescheduling is necessary to reschedule trains to reduce hindrances from the perturbed situation. This is mostly done by signallers under supervision of traffic controllers. There are different aspects of rescheduling which can lead to a good result. Signallers mostly follow the local priority rules in the train dispatching documents (TAD) when rescheduling. The manual behaviours might be translated to automated systems. The following actions can be undertaken in case of rescheduling which are further described thereafter: reordering, rerouting, retiming and even the more sophisticated speed advices to the train driver (Luethi et al., 2009; Albrecht and van Luipen, 2006).

Reordering

When a train is delayed, which can cause a conflict with following trains, reordering is a typical measure. Especially when the delayed train is slower, by having a more dense halting regime, it can be really useful to reorder in order to minimize secondary delays. When two trains are heading for the same same destination it is important to dispatch trains in an optimal order to avoid slow trains causing hindrance for high speed trains. A negative effect could be that transfer connections could get broken by reordering the trains, which might minimize train delays, but does create passenger delays. Reordering can only be done at junctions or stations since this tool requires switches and often even extra tracks for overtaking. In this particular case, reordering is most interesting at the track-merging locations, because there the order of trains is decided. Rules for reordering are based on prioritisations, which can be done in different ways, summed up below:

- No prioritisation (first comes first served, like in today's DVM)
- Train type (german model)
- Destination (giving long-distance trains priority)
- Current delay (often done in manual dispatching)

When choosing between the different prioritisations it is important to keep the goal in mind. To steer on throughput is the main goal for the Schiphol tunnel, as it is a bottleneck. Secondly the XPTs are rather important due to the wishes of the operator(s) on the tracks. Within the area where the DVM should function, trains run rather homogeneous as they all halt on Schiphol, however differences are to be seen in dwell times. This could mean reordering by train-type could be valuable at Schiphol. The location based prioritisation finds its origin in the amount of time a train runs delayed. A train ending near Schiphol is suffering a much shorter time from delays than long distance trains. An alternative is to let the current delay decide what the order should be. It can be useful to avoid large delays of trains. Although letting an on-time train wait where one wants to steer on throughput probably does not give a desirable effect. An extra constraint for the XPT might be necessary to add in the reordering rules to ensure the specific connections, if the connection still would make sense.

Rerouting

Within stations and at triple or quadruple tracks it is possible to reroute trains due to available parallel alternatives. At the today's DVM only the cross-platform switch can be considered as a rerouting measure because of its dynamic routing rules. Rerouting can be particularly useful to avoid conflicts between trains so prioritisation is not even necessary. At Schiphol, dynamic routing can also give some great opportunities concerning utilisation of capacity. For each and every train there are only a very limited amount of routes available due to the 'simplicity' of the infrastructure and the constraints concerning platform usage. This means real-time conflict detection by a DVM system is theoretically not even needed. Due to the limited options at the Schiphol case, a conflict matrix can show all the possibilities. Constructing the matrix is done by determining all the possible routes and determine which combinations have conflicts, and which routes can be set parallel. An example table is shown in table 3.1 with corresponding illustration 3.8.

Table 3.1: A simple example of a route conflict matrix, checking two routes for a possible conflict. **1** = conflict, **0** = possible, **-** = impossible combination

	A-C	**A-D**	**B-C**	**B-D**
A-C	-	-	1	0
A-D	-	-	1	1
B-C	1	1	-	-
B-D	0	1	-	-

Routing in the Schiphol tunnel depends on the platform use which is constraint to the origin and/or destination. Westbound for example the trains have three directions: the high-speed line, the branch to Leiden and the yard of Hoofddorp. Trains starting/ending at either Hoofddorp or Schiphol will all come

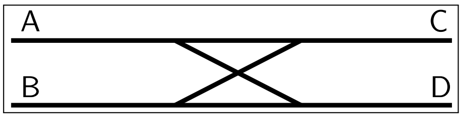


Figure 3.8: Corresponding illustration to the matrix in table 3.1.

from / go to the yard of Hoofddorp, meaning they preferably use the inner tracks and therefore platforms 3/4. For high-speed trains, the opposite is true: the outer tracks should be used in combination with platform 1/2 and 5/6. The Leiden-branch can be easily accessed from all tracks. Due to this constraints in routing, options are very limited already. Rerouting should be done with respect to the passengers. It cannot be the case that they should go to other platforms. The dynamic use of both sides of a platform is not a problem.

Combining rerouting with reordering creates a powerful tool: overtaking. Overtaking can be interesting to use at a specific location, being the railway station itself of Schiphol. There the earlier mentioned heterogeneity strikes as dwell times between trains differ. By allowing overtaking at Schiphol controlling the railway operations gets more complex, but could theoretically mean better utilisation of the capacity by reducing waiting times for trains with low dwell times. This is theoretically a nice idea, but hard to implement as one wants to leave as quick as possible after alighting and boarding has taken place. To arrange this extra hardware would be needed on the platform to give conductors the possibility to signal the system that the train is ready to leave, costing extra time. This system is for example used a lot in Germany.

In the model the focus of rerouting is mainly based on the concept and not on the technical systems behind it.

Retiming & speed advices

There is lack of a clear definition of retiming in rescheduling in railway operations. For this case the following definition will be used: On purposely increase the dwell time at a station or driving times on the track to provide a smoother service later on, en route. This is very similar to the traffic management solution in road traffic called ramp-metering. By postponing the moment when a vehicle (or train in this case) enters the bottleneck a traffic jam might be avoided. By delaying one train one tries to minimize the delay of one or multiple other trains.

Giving speed advices to train drivers is a retiming tool. It is done none discretely like dwelling longer at a station. In fact this is not steered upon by means of the signalling system, the retiming takes place smoothly and additional equipment is required. Nowadays this measure is barely used in train control as this requires intensive contact with train drivers which nowadays primarily takes place by phone. Developments in ERTMS will create new possibilities for this rescheduling tool because a permanent communication system for the train drivers and traffic control is part of the system. This system shows a lot of similarities with air traffic controlling and the line-up for landing. By adjusting speeds of the aeroplanes the controllers create a zipper effect causing a perfect spacing between them before merging as illustrated in figure 3.9 for trains. This saves one or more trains waiting for a red signal and keeps capacity utilisation high. Besides that it is also more environmentally friendly as trains consume less energy by saving a stop and an acceleration. Other recent developments in the Dutch system consist of Routelint (bron), which is also a form of giving advice to the train driver. Based on the information of trains in front and behind the train, the driver can smartly adjust his speed.

Because of uncertainties in the future use of this feature, and the complexity of modelling it, it will not be taken into account in the simulations. The retiming as whole will be implemented, leaving a choice in the end, how to execute this rescheduling element.

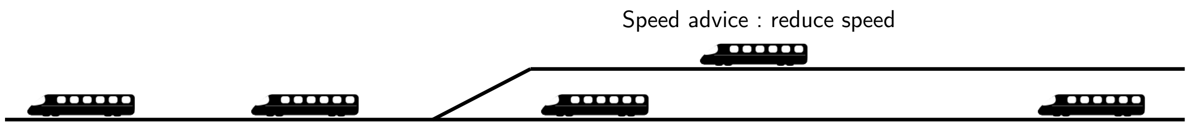


Figure 3.9: Zipper effect with merging trains. With speed advices, the right distances can be created for smooth merging. This can save two trains to stop.

3.3.3 Forming the DVM

Introduction

The above mentioned tools of rescheduling can be automated to create a DVM system, which is basically a rule-set as a layer over the regular system. There are several combinations possible for these DVM-tools forming different alternatives. All random combination can be thought of, but not all make sense. For example the reordering is a crucial part of the system, without that it could not function properly in case of perturbations. For example because merging trains would have to wait for their predecessors in case of a late train from the other branch. The remaining solutions are combinations of reordering with the other rescheduling tools. In table 4.3 the analysed combinations are mentioned.

Combinations

Table 3.2: Combinations of (automated) controlling rescheduling tools

Combination:	Reordering	Rerouting	Retiming
1.	x		
2.	x	x	
3.	x		x
4.	x	x	x

Today's DVM reorders trains based on FCFS instead of according to a scheduled plan. Furthermore the cross-platform switch (XPS) could be seen as a form of rerouting but routing would be a better term as trains are not routed at first. Retiming measures are not taken at this moment as one strives to have a high throughput in the Schiphol area, but retiming may prevent a conflict and could thus also be beneficial for the throughput. Concluding one could say that the actual DVM is a tool which reorders and reroutes (combination 2 in table 4.3).

Functioning of the DVM

The DVM is a set of rules which are automatically applied to the regular controlling system, if summarised. There are three key features within such a system: thresholds, a set of rules and steering areas (illustrated in figure 3.10). Thresholds are needed because the rules have to be applied two blocks before a steering area because the interlockings need to adapt on time. Rules are typically conditional, meaning that they mainly consist of 'if...else statements'. A simple example is the the FCFS algorithm:

> **If** train X passes threshold X earlier than train Y passes threshold Y **then** train X goes first **else** train Y goes first.

They can include more conditions to meet, to customise the system for the wished effects. For example timely dependencies, detailed prioritisations and the XPT relation. Reordering, retiming and rerouting can all be translated to such statements. Preferably the amount of rules are kept to a minimum to ensure the understandability for signallers who are monitoring the system.

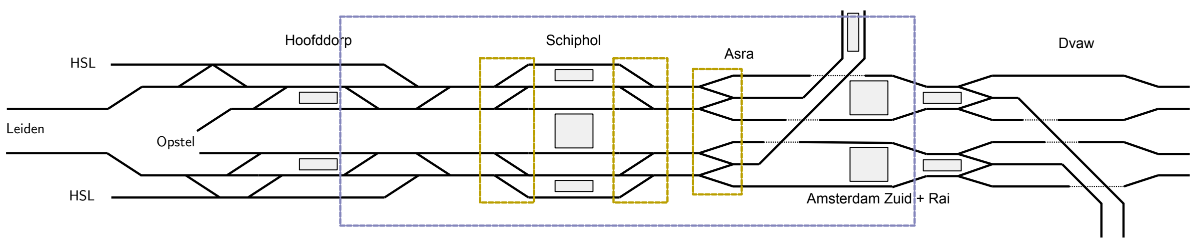


Figure 3.10: Overview of the 2018 Schiphol railway network. The large, blue area shows the control area of the DVM system. The smaller, orange areas show the steering areas.

3.4 Summary and conclusion

The railway infrastructure manager (ProRail) and the railway operators (NS, NS Hispeed) are mainly acting on behalf of the passengers. ProRail also strives to optimally use the capacity of their infrastructure. NS is servicing above all the passenger with comfortable, reliable, fast and high frequent train services with only a small amount of transfers. As mentioned in the previous chapter: it is hard to combine all of them. Especially for ProRail serving more players in the field. A DVM system should fulfil requirements of both parties, consisting of being safe, able to handle the timetable stably (also in perturbed situations), automated and controllable. It should also be simple and understandable. A new DVM system is mainly needed to be able to handle cross-platform transfers. Today's system isn't capable of handling these due to the existing cross-platform switch and the keeping your lane principle. The DVM should be able to reschedule because trains do not always enter its working area punctually. Rescheduling consists of three elements: reordering, rerouting and retiming. To be able to cope with trains entering on different moments in time, the reordering element is a must for the system.

Chapter 4

Model

When a track section has apparent capacity shortage, it is costly to improve it with infrastructure expansions. It is common to analyse the utilisation of capacity to see whether there is capacity left by scheduling and controlling in a smart way. In this way constructing new railways can be postponed or not constructed at all. This can be partly done with calculations, but to have a fair idea of how railway traffic interacts in specific cases, it is wise to test it in order to include stochastic effects as well. This could be done directly in real-life with full-size tests, but these are costly and can cause hindrance for passengers. Computer simulations can be a way to avoid any waste of money by using a model of the specific case. This has great money saving and hindrance avoiding advantages, but has it's downsides too. Models are always inaccurate to some level. Therefore they need to be calibrated and then validated to ensure a sufficient representation of reality. Afterwards often still on-site tests are executed to analyse and find out any non-expected effects of the new measures. There are several railway simulating tools in use nowadays but mostly developed and kept internally by railway companies and infrastructure managers. A limited amount of software is available on the market whereof OpenTrack is a commonly used one in Europe. Because of its compatibility with the railway-data standard "RailML" and its wide variation of possibilities, it's a convenient tool for the Schiphol case.

4.1 Introduction to simulation in OpenTrack

OpenTrack is developed at the Swiss Federal Institute of Technology in Zürich at the Institute of Traffic Planning and Transport Systems (ETH IVT). As a spin-off it developed to a commonly used commercial and academic product. It is a tool for microscopic railway simulation where detailed information is needed as input with a result which is highly detailed as well. OpenTrack is an object oriented program which has benefits for both calculation time and user-friendliness (Nash and Huerlimann, 2004). An overview of how OpenTrack globally is working, is visible in figure 4.1.

4.1.1 The software

An OpenTrack model globally consist of the following three inputs: infrastructure, rolling stock, and timetable data. These are all illustrated in different ways. Infrastructure needs to be set up first by either importing it or drawing a network by hand. The tracks are modelled in a double vertex graph system (figure 4.2b) which consists of pairs of vertices connected by lines. Both the lines as the vertices carry valuable information about track segments (lines) and objects as speed signs, signals and switches (vertices). The double vertices cause the model to force trains in the right way through a switch. In a classical graph representation (figure 4.2a) the train might end up driving from branch to branch although this is impossible in the real world.

Safety elements, signals and other infrastructure data are complemented with possible routings of a train. As soon as rolling stock data is implemented and schedules are created the simulations can start. With a view which is rather similar to that of a traffic controller one can see trains using the tracks and observe any conflicts which might exist in the schedule accidentally. All data of a simulation can be stored for further processing or in-program plots can be obtained to visually spot difficulties in the

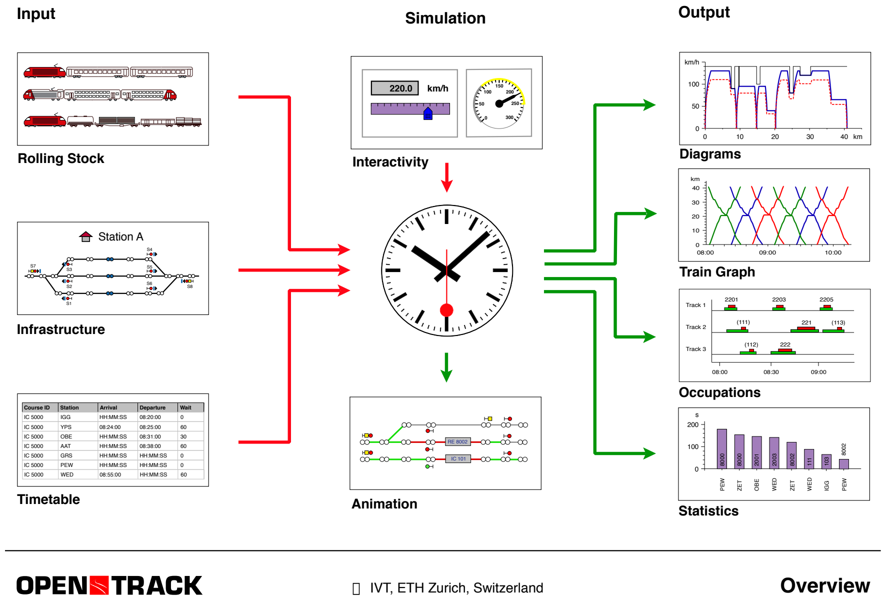


Figure 4.1: Overview of the functionalities of OpenTrack with the required input and the produced output (Huerlimann, 2013).

(a) Single vertex representation of a switch which could give problems while simulating

(b) Double vertex representation of a switch which is used in OpenTrack

Figure 4.2: The different representations of a switch in a graph system (Huerlimann, 2003).

virtual railway operations. OpenTrack consists of several of these outputs like a blocking time diagram with conflict detection, speed profiles and track occupation graphs, which are all powerful tools for analysing capacity utilisation of railways. Especially in more complex environments like the Schiphol area, this tool gives a lot of insight in train operations.

4.1.2 Input-data

The data required for OpenTrack consist of detailed information about the tracks, rolling stock and the timetable. When studying a rather large area the amount of data is equally large which could cause a lot of work. Fortunately most data does not need to be inserted by hand but is available in digital datasets. This section will explain how the data for the Schiphol case is obtained.

Infrastructure and route data

All tracks managed by ProRail are well documented in so-called 'overview of track and yard sheets' or simply OBE-sheets in Dutch. These give a schematic representation of the location and identification of all infrastructure elements, speed restrictions and other special remarks. OBE-sheets are used for multiple purposes, ranging from asset management to route knowledge for drivers. In a digital form all this information is also available in the InfraAtlas in a database-format, solely used within the company. The dataset is updated regularly to adapt to changes in the real-world infrastructure and is an input for multiple internally used tools. By obtaining an export file of the InfraAtlas the infrastructure can be processed to RailML(+) for use in OpenTrack. This is described further on in section 4.1.3, where the conversion is elaborated on. An example of a part of an OBE-sheet is shown in figure 4.3

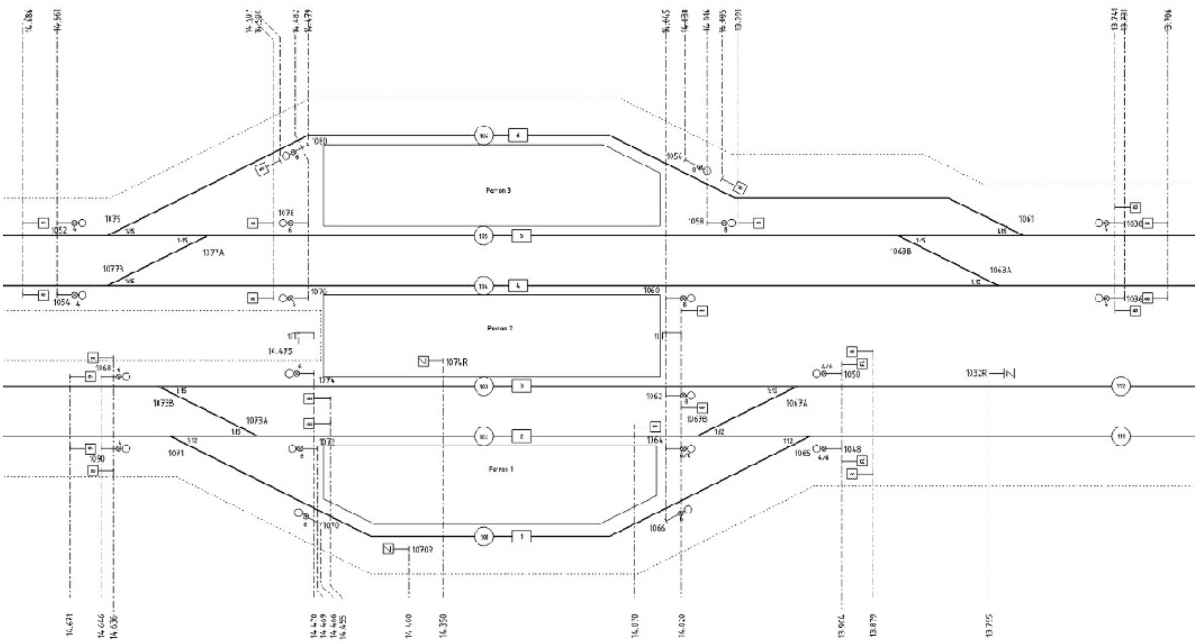


Figure 4.3: Example of a part of an OBE-sheet, of Schiphol (NS / ProRail).

Rolling stock

OpenTrack's most sophisticated feature is the train dynamics simulation. By known formula's from literature the software reproduces the driving behaviour of trains very accurately over the virtual tracks of the model with certain time steps (1 sec in this case). The necessary data roughly consists of the length, weight, power and adhesion of a train. With those parameters one can calculate a traction-force curve (figure 4.4) which describes the power to accelerate. At lower speeds this is determined by the adhesion of the powered axles, where at higher speeds the engine capacity defines the limit.

Traction force (Adhesion limit), line A in figure 4.4

The acceleration at lower speeds is determined by the grip a train has on the tracks. The interaction between rail and wheels is depending on the force on the wheel. The adhesion factor is mostly found empirical and mostly between 0,1 and 0,3. In case of an unknown adhesion factor the assumed value is 0,143 (Delft University of Technology, 2011).

$$T \leq \mu G_{adh}$$

T = Traction Force [kN]
μ = Adhesion factor [-]
G_{adh} = Weight carried by powered axles [kN]

Traction force (Power limit), curve B in figure 4.4

As soon as speeds are higher the traction force is dependant on the power and the efficiency of the engine(s). The following formula describes the transformation of power into a force.

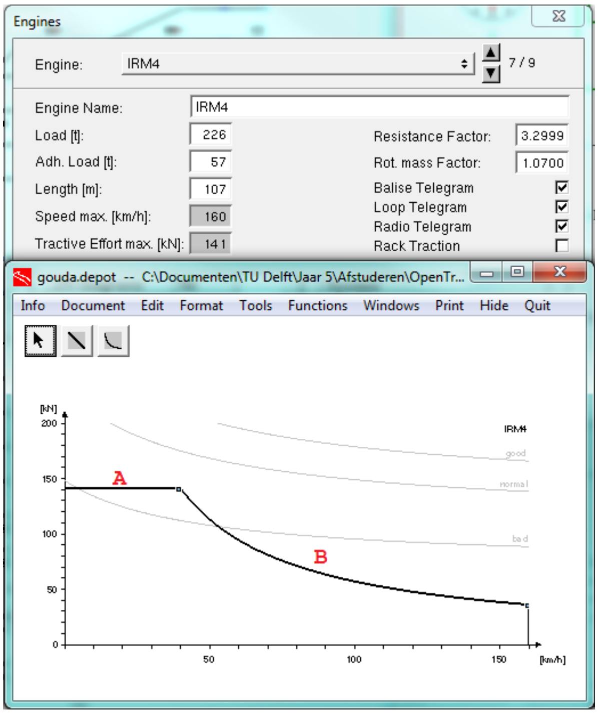


Figure 4.4: Example of what the rolling stock data looks like in OpenTrack, with the entry fields of the basic data and the traction-force curve. A is the traction-force limited due to adhesion, and B is limited by the engine power. (OpenTrack).

$$T = \eta \left(\frac{P}{v} \right)$$

η = Energy conversion efficiency [-]
P = Power [kW]
v = Speed [m/s]
T = Traction Force [kN]

Engines and Trains

In OpenTrack one has to insert the data of the engines, or nowadays the more common electric multiple units (EMUs), manually. To build a formation one needs to select multiple engines, one or more EMUs or carriages. These formations can be assigned afterwards to a specific course and itinerary. Some assumptions are made about the future use of trains. For instance all the international high speed trains are assumed to be carried out with Thalys trains, national high speed trains with V160 TRAXX trains, intercities with double deck trains and the local trains with SLT material.

Table 4.1: Train formations

Abbreviation	Formation	Type	Length [m]	Weight [t]	Usage in train series
SGMm	SGM2 + SGM3	SPR	131	254	Only in validation
SLT 6	SLT6	SPR	101	192	4200, 4300, 4500, 4600
SLT 6+4	SLT6 + SLT4	SPR	171	336	4100, 4400
VIRM 6	Virm6	IC	107	226	3100, 3200, 3300, 3900
VIRM 6+4	Virm6 + Virm4	IC	188	402	1200, 1300
TRAXX	Traxx loc. + 6 Carriages	HrST	175	331	200, 300
PBKA	Thalys PBKA	HST	200	416	100

Timetable

The timetable for the future is only roughly known as it only consists of a concept service pattern. A certain amount of assumptions have to be made here, with a logical sense of planning. Due to the amount of trains with limited infrastructure and the typical periodicity of the timetable, a lot of constraints apply, making it rather predictable. The timetable needed for validation is known and will be implemented in the model. The model borders are not directly at a station, which requires an additional timestamp in the schedule. In the validation process of the model the time needed between the borders and the next station are found by means of iteration. It is not possible to convert a timetable - unless delivered according to certain standards - automatically to the OpenTrack format. The timetable of today's situation for validation is implemented manually.

The future timetable is showed in figure 4.5. It is based on a concept of frequencies, the cross-platform transfer connections and minimum headways between trains. All these constraints for the timetable are described in table 4.2. Developing the timetable for 2018 could be an individual thesis itself already, therefore some assumptions are made. This result in an almost conflict-free timetable which does not directly take into account conflicts outside of the model. Any minor conflicts and resulting delays within the model, in a perturbation free situation, are traced and assigned to individual trains. These delays are corrected at the measuring of the performance of the DVM concepts, to eliminate the fact that the schedule might not be optimal. The DVM concepts are compared relatively to each other. Therefore a not 100% correct timetable won't make the difference in the relative performance of the DVM concept.

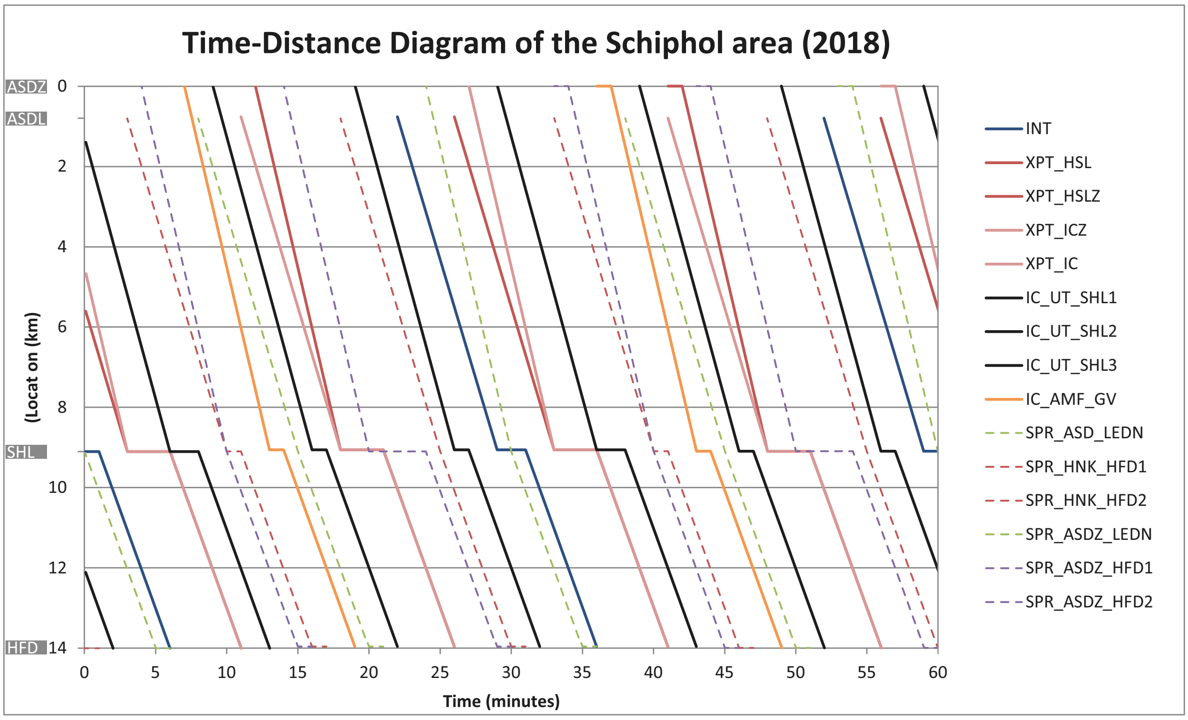


Figure 4.5: Possible timetable for the future situation including the XPT. The abbreviations of the train series are explained below in table 4.2. The timetable is showed in the form of a time distance diagram where the branch from Amsterdam Zuid and Amsterdam Lelylaan are plotted on top of each other.

Table 4.2: Assumed future timetable

Nr	Series Name	Type	Origin	Dest.	Freq.	Remarks
100	INT	HST	Asd	Brx/Par	2x/h	Thalys to Paris or High-speed Train to Brussels
200	XPT_HSL	HrST	Asd	Rtd (Bd)	2x/h	Has a XPT with the 1200 15 minute alternation with 300
300	XPT_HSLZ	HrST	Zl (Gn)	Rtd (Bd)	2x/h	Has a XPT with the 1300 15 minute alternation with 200
1200	XPT_ICZ	IC	Zl (Lw)	Drd	2x/h	Has a XPT with the 200 15 minute alternation with 1200
1300	XPT_IC	IC	Asd	Drd	2x/h	Has a XPT with the 300 15 minute alternation with 1300
3100	IC_UT_SHL1	IC	Ut (Hrl)	Shl	2x/h	Forms a 10 minute interval with 3200 & 3300
3200	IC_UT_SHL2	IC	Ut (Nm)	Shl	2x/h	Forms a 10 minute interval with 3100 & 3300
3300	IC_UT_SHL3	IC	Ut (Ehv)	Shl	2x/h	Forms a 10 minute interval with 3100 & 3200
3900	IC_AMF_GV	IC	Amf (Es)	Gvc	2x/h	
4100	SPR_ASD_LEDN	SPR	Asd	Ledn	2x/h	Forms a 15 minute interval with 4400
4200	SPR_HNK_HFD1	SPR	Hn (Hnk)	Hfd	2x/h	Forms a 15 minute interval with 4300
4300	SPR_HNK_HFD2	SPR	Hn (Hnk)	Hfd	2x/h	Forms a 15 minute interval with 4200
4400	SPR_ASDZ_LEDN	SPR	Hvs (Ut)	Ledn	2x/h	Forms a 15 minute interval with 4100 & Forms a 10 minute interval with 4500 & 4600
4500	SPR_ASDZ_HFD1	SPR	Alm (Lls)	Hfd	2x/h	Forms a 10 minute interval with 4400 & 4500
4600	SPR_ASDZ_HFD2	SPR	Alm (Lls)	Hfd	2x/h	Forms a 10 minute interval with 4400 & 4600

Around Schiphol both 10-minute- and 15-minute-corridors come together where trains have a corresponding interval. Combining these two with alternating services cause intertwined dependencies with irregular intervals for passengers. For example, one can travel every 10 minutes from Amsterdam Rai to Schiphol, but only every 15 minutes by Sprinter from Schiphol to Nieuw Vennep. For passengers this means, that they have every 30 minutes a direct connection between Rai and Nieuw Vennep, while the next connection with the same origin and destination departs already 10 minutes later with a 5 minute transfer at Schiphol.

Initial delays

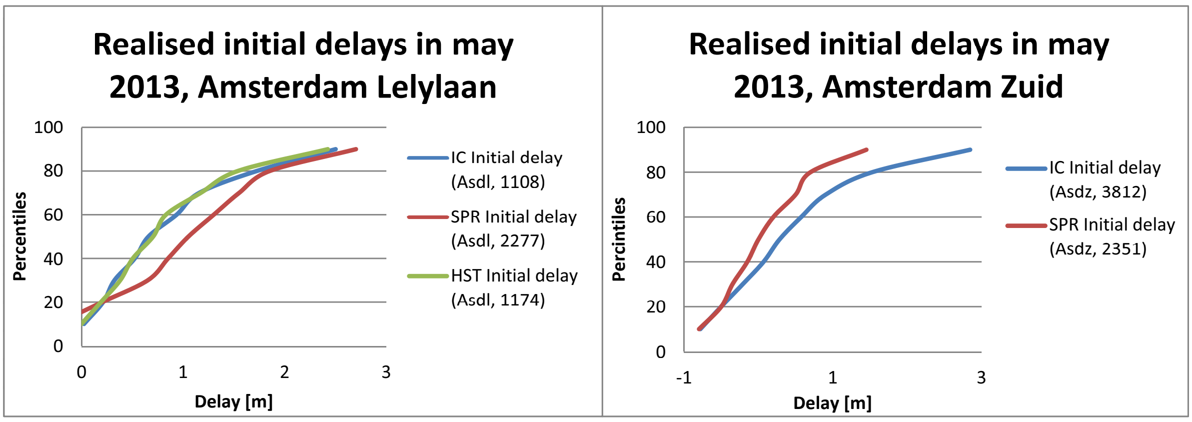


Figure 4.6: Realised initial delays in may 2013 measured at Amsterdam Lelylaan and Amsterdam Zuid. Displayed per train type, including the total amount of trains measured. (Data from ProRail and NS)

4.1.3 Conversion

As earlier mentioned, most railway companies use their own standard for storing data. To be able to use the data for other (commercial) software a conversion is needed tot the international standard RailML. To convert InfraAtlas data to RailML and RailML+, IA2OT is developed.

IA2OT

The name of this software is literally an abbreviation for InfraAtlas to OpenTrack, stating almost exactly what it can do. The tool functions in a couple of steps. First it has to read the InfraAtlas file, which is actually an exported file from the whole Netherlands from the InfraAtlas. Mostly this step can cause some trouble as the InfraAtlas might contain some double lines in the script. These are infrastructure elements which are accidentally defined twice. These double lines can be easily removed by either an automated program, or by manually removing the lines as IA2OT gives the line number in the error. In this specific case only one line was a double. After the file is loaded in the program it can show you a full list of the OBE-sheets and their interconnections in visualisations. These visuals give you the opportunity to create a region of OBE-sheets which are wished to be exported to OpenTrack. After setting up a region, preferably not too big to avoid an overfull workingsheet in OpenTrack, one can export these to RailML and RailML+. RailML can be imported in OpenTrack for the infrastructure data. The RailML+ file contains the routes and different signal indications which can be imported after the infrastructure data.

4.1.4 Further adjustments

Both the conversion from InfraAtlas to OpenTrack and the InfraAtlas data itself are not totally impeccable. Especially the track speeds are full of mistakes. To correct this the original OBE-sheets are used, which sometimes still contain little errors. As a final measure everything is double-checked by means of recent recorded cabin rides, easily found on the internet (YouTube [1]). This is a time consuming process as every single edge of the model needs to be checked.

In this particular case the model is too large to put on a single worksheet in OpenTrack. To avoid an overfull worksheet the model is split in three parts. The lacking connection between the sheets initially cause some data loss as routes including signal aspects are not automatically implemented any more. After reconnecting the sheets in OpenTrack the routes need to be reset manually.

4.2 Performance indicators

In order to analyse and compare alternatives of the DVM rule-sets the performance needs to be defined. This is done by means of performance indicators which comprehensively try to describe the alternative. The indicators are determined based on the requirements of the different stakeholders and from preceding researches described in literature. A main characteristic of a performance indicator is that it should be measurable in an objective way. Preferably one uses a non arbitrary scale such as SI units or derivatives of it. Percentages can give insight in performances as well.

[1] https://www.youtube.com/watch?v=CXVxD5q9u7c

4.2.1 Introduction to performance indicators

To obtain the right indicators the goals set must be clear. Important for the DVM system is to steer on throughput, which means to steer on capacity. The timetable is given, resulting in that one has to measure a derivative of the capacity: delays and the recovery of them. Furthermore the capability of maintaining the Cross-Platform will be a key performance indicator.

For this case the following three indicators are chosen for comparison:

- Recovery of delays, stability
- Maximum delays
- Cross-Platform Transfer ability

Recovery of delays / stability

All trains will enter the system with (a distribution of) an initial delay. Due to interaction between trains an initial delay can be passed on to other trains resulting in more delays. In case of good controlling the delays will get smaller over time, evidencing of a stable system, with sufficient capacity. If delays are getting larger over time the system is unstable and therefore not a feasible solution. The accumulated delays within the model will be the most important performance indicator of a new DVM. This will be measured at the place where a train passes or halts at the last station within the model. The accumulated delays (minutes) divided by the amount of trains gives the final value for this indicator, which can be negative when the system reduces delays. Because the main objective of a controlling algorithm is a stable system with a minimum of delays, this indicator will have the highest relative score in the later comparison of the alternatives. A mathematical annotations to specify this, would be:

$$\sum_{i=1}^{n} \frac{t_{i,exit} - t_{i,entry} - t_{i,correction}}{n}$$

$t_{i,exit}$ = Time that train i exits the model [s]
$t_{i,entry}$ = Time that train i enters the model [s]
$t_{i,correction}$ = Time that train i needs in the simulation without initial delays [s]
i = Train (index)number [-]
n = Total number of trains in the model [-]

Maximum delay

While automatically dispatching trains, to reduce the cumulative delays, it can happen that in general delays have decreased, but that single trains are being duped. Therefore it will have added value to also observe the maximum delay. From a passengers perspective it is highly frustrating if other trains can pass and your train has to wait. To filter out the case of single trains having large delays this indicator will play a minor role as well. One could implement a rule in the system, which only allows a maximum waiting time. To keep the system as simple as possible, it is left out and will be seen as a performance indicator. The unit used for measuring this indicator will be seconds. One should realise that the value is based on a single train in 30 runs and probably an outlier. It only illustrates an (unrealistic) worst-case-scenario.

Cross-platform transfer

Not every algorithm will be able to maintain all Cross-Platform Transfers. Threshold-times will have to be stated for what time it is reasonable to hold a train for a XPT. Typically this time is very short in dense and high-frequency networks. In case of a longer disrupted service this leads to a certain percentage of transfers (not) kept. Resulting, a comparable value for the cross-platform transfer will appear. As an indicator it is of a relatively high importance because of the requirements of the operators. Without a stable XPT their service pattern wouldn't make sense to their customers.

Understandability

The understandability is formally not a performance indicator as the result is not an outcome of the simulation. It is just a property of a system, but will be used in the comparison of the variants. From the wish of ProRail the desire exists to have an (easily) understandable system. In order to objectively quantify this property, the amount of rescheduling elements are taken into account. So by simply counting the amount of elements one could determine a grade of complexity which will serve as an indicator for the variants.

Overview

The following table gives an overview of al indicators and the understandability, their units, expected range and their relative importance. The latter one can later be used as a guideline for scaling when a comparison is made between the alternatives in chapter 5.

Table 4.3: Overview of the performance indicators

Indicator	Unit	Outcome range	Relative importance
Delay	seconds/train	0+	1
Maximum delay	seconds	0+	3
Cross-platform transfer	percentage of transfers kept	0-100	2

4.3 DVM scenario's

In chapter 3 four alternatives where shortly introduced. In this section they are elaborated on further to describe their rules in more detail. For all cases three different priority measures are mentioned, but only one will be used, depending on the outcome of the first case. The conflict detection algorithm is used in two of the priorities and therefore those priorities are having more conditions which are used in the complex calculation. All the DVM rule-sets are an overlay to the normal safety systems, which means safety could never be an issue because of the DVM's decision.

A short recap of the tested alternatives is showed in table 4.4.

Table 4.4: Combinations of (automated) controlling rescheduling tools

Combination:	Reordering	Rerouting	Retiming
1.	x		
2.	x	x	
3.	x		x
4.	x	x	x

4.3.1 Case 1 - only reordering of trains

The most simple alternative consists solely of reordering trains. This first variant will however also handle different subvariants of the prioritisations. The best of the prioritisations will also be used in the further alternatives.

Prioritisations

Only four different prioritisations will be tested, as they seem to be the most logical ones to give good results for the Schiphol case, where throughput is the main aspect to steer on. The second and the third are based on a fixed hierarchy.

- First comes first served
- Train type : local, intercity, national 'high-speed' (v160), international high-speed (v300)
- Final destination : ending at Schiphol or Hoofddorp, Ransdstad area, Rotterdam or further within NL via HSL, International trains
- By largest delay

For the first one the conventional single threshold system is sufficient for the system to work. For the other prioritisation concepts only two trains can be compared as soon they pass the conflict zone within a certain time frame. This means first a reporting threshold is needed, to be followed, in a distance of about 90 seconds driving time, by a second threshold. Together the thresholds form a 'threshold zone'. This gives the system the chance to decide which train goes first. 90 seconds is about the technical minimal following time of two trains. Therefore this is chosen as the 'distance'. The system is illustrated in figure 4.7. In case of equality between trains within a prioritisation rule the FCFS rule applies.

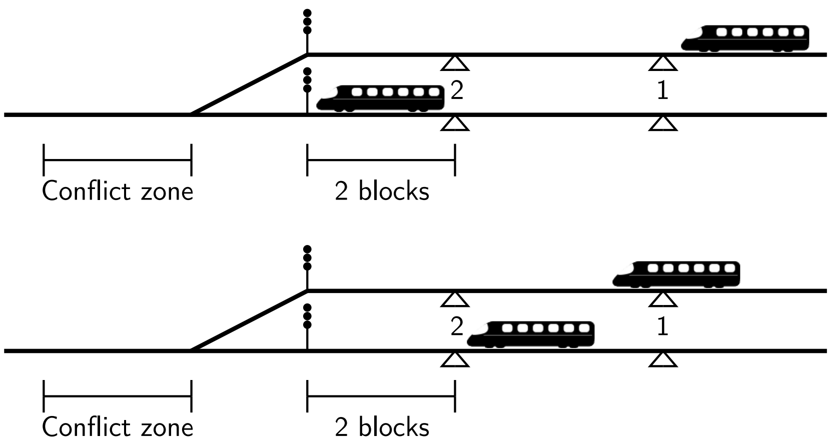


Figure 4.7: The double threshold system for prioritisation. The first situation does not require prioritisation, the second one does.

Model

The rules of prioritisation can be based on a series of 'if...else' statements. For example: "IF Train x passes threshold x_2 earlier than train y passes threshold y_2 Train x goes first ELSE Train y goes first". For modelling in OpenTrack these rules are implemented already in the software. One namely has to chose the dispatching algorithm for signals. Some of the options are: FCFS, biggest delay and train category. The latter one can be manipulated for use for the hierarchy based prioritisation like the train type and train destination just by classifying the train series in the right categories. For the FCFS no extra settings are needed. The other three require for the earlier described double threshold an extra 90 seconds so-called look-ahead time, which can also be specified in OpenTrack. The choice of prioritisations is visible in figure 4.8.

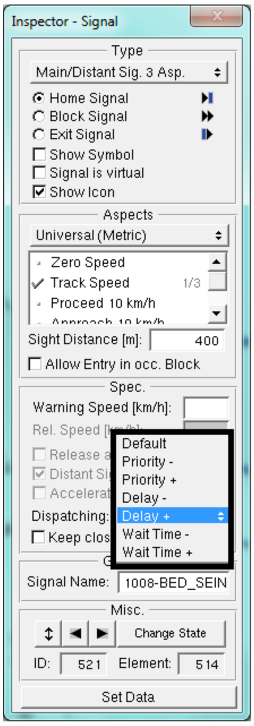


Figure 4.8: The settings of a signal in OpenTrack where prioritisation can be determined for the route setting in case of a conflict.

The three train problem

In case of multiple trains following each other up at a conflict area, it can happen that directly after a train had to 'give right of way' another conflict occurs. Depending on the prioritisation concept the train might have to let the other train go first again resulting in a longer waiting time at a conflict. Theoretically this could lead to endless waiting. In praxis one could give a maximum waiting time as an extra rule to a DVM system. On purpose this is not implemented in these simulations as it is also very interesting to see what the longest delay could be of the DVM system. Due to the stochastic effect in the delay, there always is a gap for a train within a respectable time to avoid endless waiting of trains.

4.3.2 Case 2 - reordering and rerouting of trains

The combination of reordering and rerouting has already proven its value. Because in this alternative the DVM system is more or less capable of doing the same as today's DVM. This means that some trains can use two sides of a single platform (the cross-platform switch) and prioritisation will take place in case of conflicts.

Rerouting

The rerouting possibilities can be described in a scheme for technical purposes. Every train has one, two or three routing possibilities for each section. If the first choice is occupied, it will try the second choice, if that one is occupied too, it will try to take the third. In the worst case the train has to wait. In case two trains are in the threshold zone at the same time, the rerouting system will look for parallel possibilities. If these are not available the prioritisation algorithm will solve the issue.

Model

In OpenTrack the rerouting is being modelled based on a hierarchy of itineraries. The implementation in the model is showed in figure 4.9. There is a preferred route for each train, and at some decision points it can choose an alternative route if the first choice is occupied. Only a limited amount of trains have the ability to have this choice. For example trains ending at Schiphol airport railway station can choose any platform which is available as there are no passengers waiting for them on the platform. Trains using track 5 or 6 and which are not involved in the XPT can choose either of the tracks depending of the availability, the 'cross-platform switch'. An example of rerouting possibilities is shown in figure 4.10.

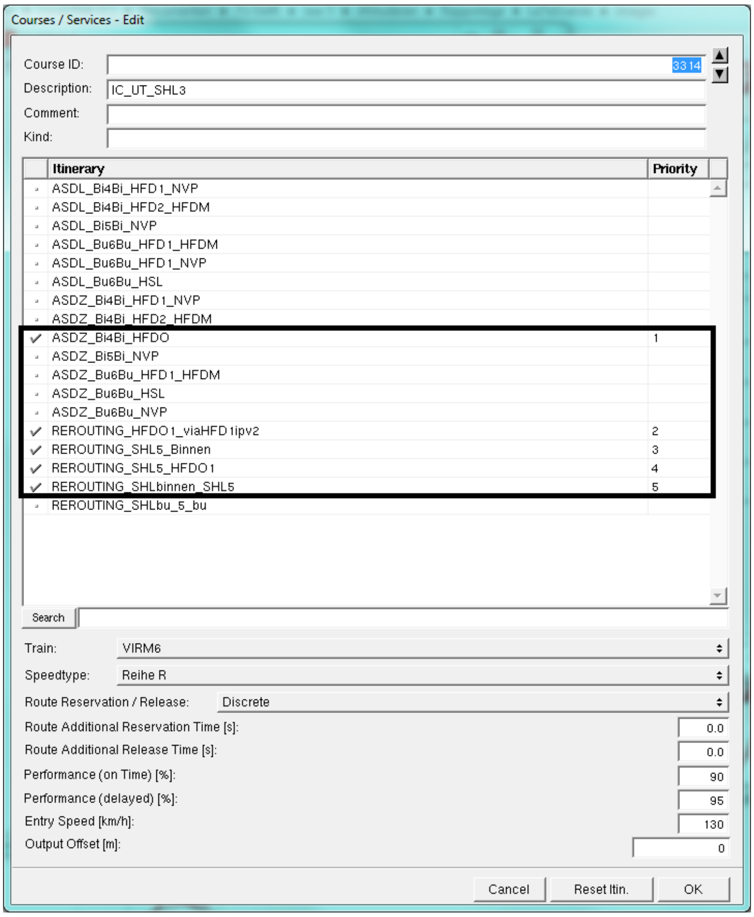


Figure 4.9: The hierarchy of itineraries in OpenTrack. As soon as the main itinerary has a route conflict, OpenTrack looks whether an alternative is available at the rerouting itineraries.

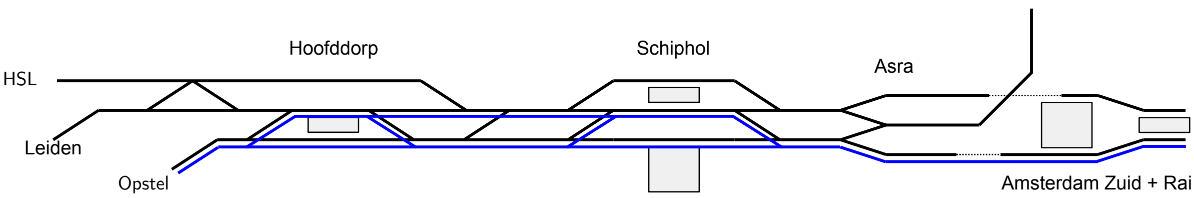


Figure 4.10: Example of rerouting possibilities for an IC train coming from the 'Zuid-as' ending at Schiphol railway station. These IC train drive further to the yard in Hoofddorp ('opstel'). In this case there are 5 possible routes.

4.3.3 Case 3 - reordering and retiming of trains

At the tracks and/or stations preceding Schiphol it could make sense to halt a train a bit longer to optimally send trains into the bottleneck. This causes better utilisation of the capacity as trains will run through green signal instead of encountering yellow and red.

Retiming in the model

There are multiple ways of implementing retiming in railway rescheduling. In OpenTrack it is almost impossible to implement a system which is capable of this feature. Therefore it is attempted to create a mechanism with more or less the same effects. By enlarging the minimum headways just before the conflict zone, the trains will have a bit of breathing space within the bottleneck. This is not literally the same as retiming in reality, but is probably the best approximation of the same effects in OpenTrack. The minimum headways before the 'Riekerpolder Aansluiting' junction are enlarged with 90 seconds by simple adding 90 seconds extra release time to the infrastructure. With this measure the chance of a conflict at the junction also rises, with is solved by the prioritisation algorithm. The implementation of this measure in OpenTrack is illustrated in figure 4.11.

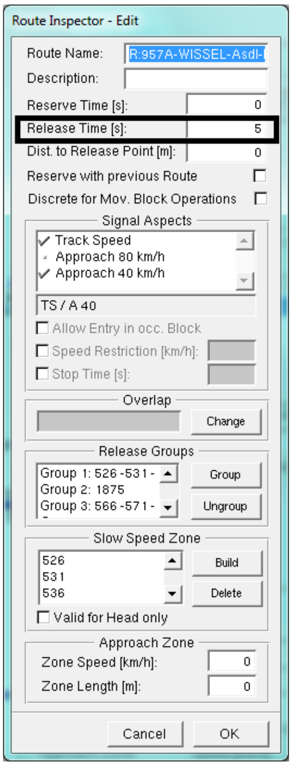


Figure 4.11: Retiming can be emulated by separating trains a bit before the bottleneck, this is done by setting higher route release times.

4.3.4 Case 4 - reordering, rerouting and retiming of trains

If one combines the prioritisations, the routing alternatives and the extra spacing of the trains with the approximation of retiming, one gets the full package of rescheduling possibilities. This results in a more complex DVM system. Really good results are needed before willing to adopt such a system.

Interactions

The prioritization in combination with the retiming generate a nice zipper-effect in cases parallel rerouting options are not available. Manual dispatching is today's only 'system' which can do what is described above. In OpenTrack the combination results in a series of adjustments described earlier in the other cases.

4.4 Validation

The validation process for an OpenTrack model is necessary to implement human behaviour correctly and therefore to proof the correctness of the model. The model is subject to a lot of parameters which cannot be determined very easily. The driving behaviour of the train driver and the dwell times on the stations are good examples of these parameters. To avoid complexity, the driving behaviour and dwell times are being implemented as a non-stochastic parameter. On the contrary the initial delays of the trains at the border of the model are represented as distribution which is known from realised data from the month of may 2013. All data is analysed per train series.

4.4.1 Stochasticity

Though multiple processes can be described by a distribution, only the delays are simulated in that way. This parameter is the least predictable and not right represented by a single value due to several reasons. Most trains have had several interactions with other trains before entering the model and also encountered other external effects. Generally the (initial) delay can be described by an exponential function, but has sometimes very specific different shapes. This varies per train series and depends on the behaviour of preceding trains. For all train series the realised delays are measured and described in 10th-percentiles also called deciles. The dwell time could be described by a (log)normal distribution with a fairly symmetric distribution. To reduce complexity and calculation times, the dwell time is assumed as a single value: the mean. Due to the symmetry the lacking of the distribution in the model will only have a minor impact. An example of the dwell time distribution of the Thalys at Schiphol airport railway station is showed in figure 4.12.

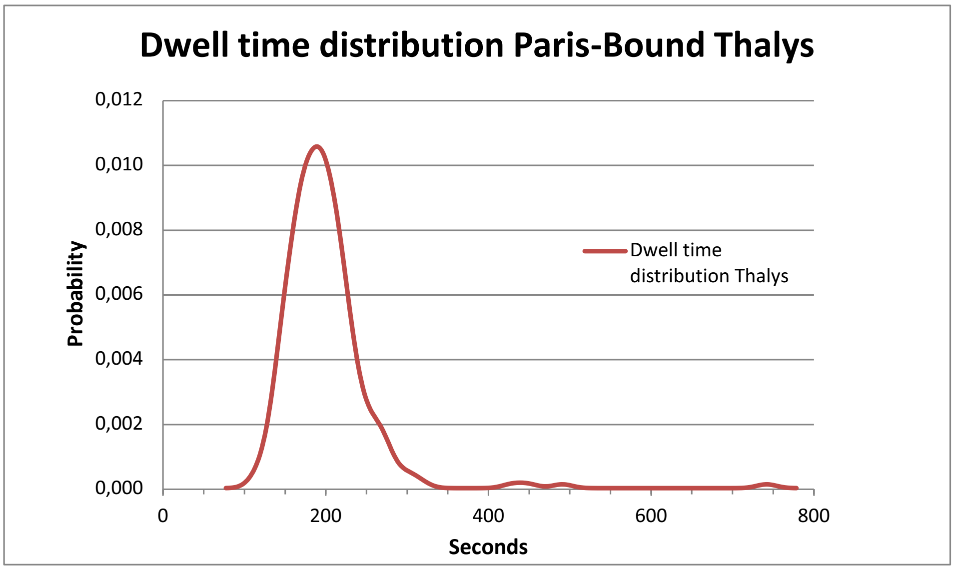


Figure 4.12: Distribution of the dwell time of the Paris-bound 9300 (Thalys) at the Schiphol Airport railway station in May 2013

Deciles

Percentiles are a way to describe a distribution in statistics, every tenth of them is called a decile. The first decile shows the maximum delay for 10 percent of the trains, the second shows the maximum delay for 20 percent of the trains and so on. In this way one can easily observe the amount of trains being 'on time' according to certain definitions. There are multiple ways of plotting the deciles. An example is shown right in the next paragraph. Although only nine specific points are known, one can interpolate between the points and connect them with a line for visual reasons. The line between the dots could theoretically almost have any shape and is therefore not accurate for in between data, but solely to ease the reading. It would not make sense to use a 100th percentile as this would simply be the highest delay of one single train recorded in the specific period of time. The fifth decile is per definition the median.

Initial delays

The entry/initial delays at the border are represented by the earlier described deciles. The realised values in may 2013 are obtained by ProRail and show clear differences in train series. In figure 4.13 and 4.14 the train series are sorted per origin: coming from the "Zuid-as" or coming from Lelylaan. In this way one can already see that both the origin and train series make a significant difference in the delay. The delay measured at these two spots are used as initial delays for the model.

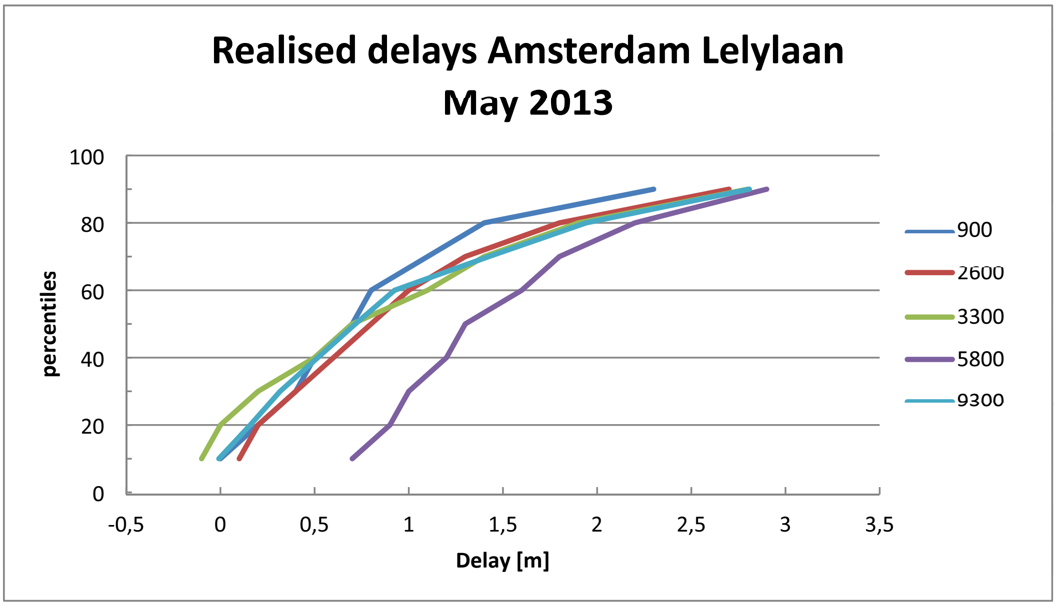


Figure 4.13: Realised delays of train series coming from the direction of Amsterdam Lelylaan (Amsterdam CS etc.) and heading for Schiphol and further.

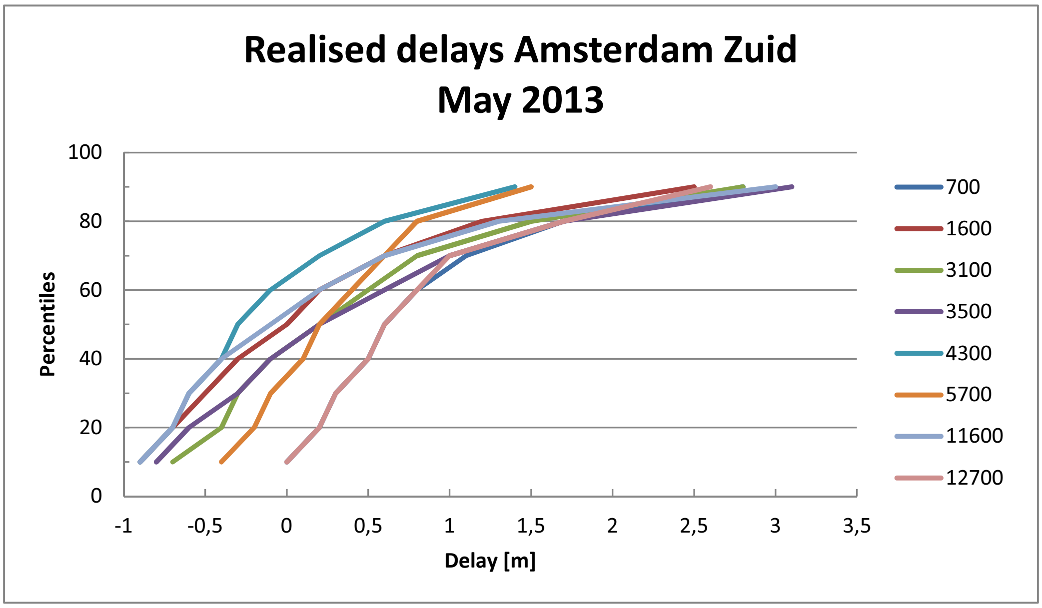


Figure 4.14: Realised delays of train series coming from the direction of Amsterdam Zuid (Zuid-As, Almere, Utrecht etc.) and heading for Schiphol and further.

4.4.2 Calibration

The process

To calibrate, one needs to adjust several parameters which are partially interacting which each other. Parameters that are used for calibration are train performance [%] and dwell time[s]. The initial delays and departure times are given from the timetable and realisation data, but were still hard to match because of non-matching model entry points. This means that departure times are entered with an offset with the proper entry-speeds in the model. This is done for each train series to assure the right start in the model. These entry-speeds are estimated, based on what is the next stop, in combination with the local maximum speed. Consecutively dwell times at the first stop are adjusted in such a way they match the realised values. The train performance which is calibrated, based on the driving times in-between stations, is the hardest to calibrate. Because this is not the only factor playing a role while driving from on to another station. Interactions between trains play a major role too. By adjusting performances of multiple train series, one can iteratively reach an approximation of the right train performance values. This is a very time consuming process, which requires more than a couple of days.

Validation results

The validation consists of 30 runs of 3:10 hours. The first 10 minutes of each run are neglected in the results as the first trains aren't having any interactions with each other. Every single run has a different random seed, which causes 30 different situation. A single run is taking more or less two minutes, resulting in about one hour simulation time. Because of the required iterative process this is a rather long simulation time. The results of the validation for arrival delays at Schiphol for all train series together are plotted in figure 4.15. In figure 4.16 these values are showed again in a different way to show that the values are quite a good fit. Since there is worked with statistical values (deciles) for comparison, it is very hard to test the match. The plots however give a quite good impression of the approximation of reality (which is actually what a model is).

Delays at Schiphol

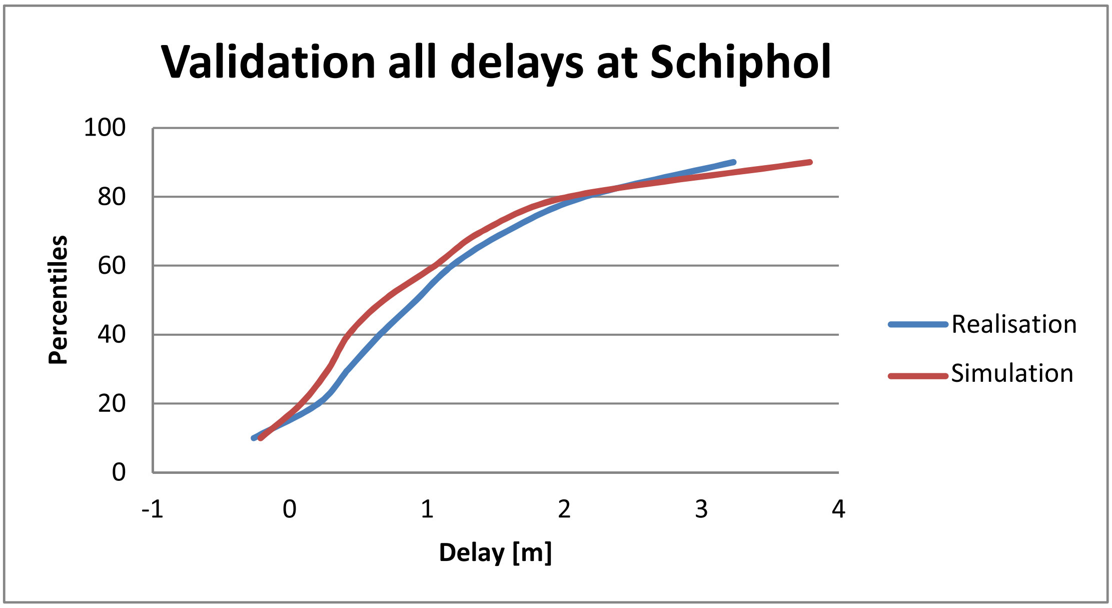


Figure 4.15: Part of the results of the validation, measured at Schiphol (all trains dwell there), showing a close approximation of reality.

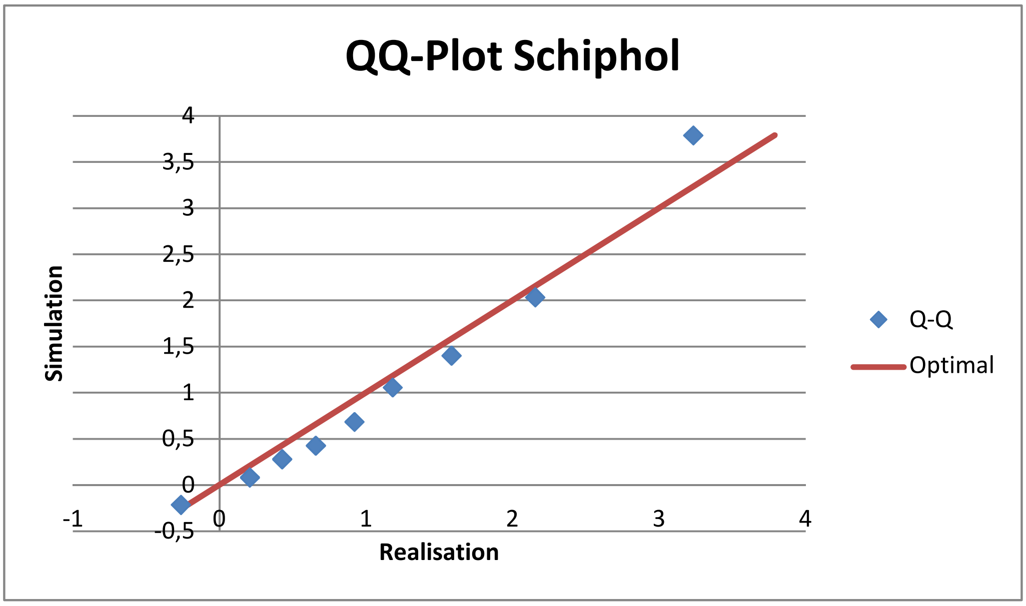


Figure 4.16: Part of the results of the validation, measured at Schiphol (all trains dwell there), showing a close approximation of reality in the form of a quantile-quantile-plot.

Parameters

The validation resulted in the estimation of some parameters which approximates the realised values. These mainly consist of the dwell times, and driving performance. The outcomes of the validation can't be one on one copied to the new model as train series disappear and new train series are created in the new schedule. Due to complete changes the values are averaged for all trains.

The driving performance consists of an on-time value and a delayed-value, both slightly different as drivers drive closer to the limits when they are late. A lot of train series in the Netherlands actually have different (scheduled) speeds on certain trajectories for on-time and delayed situations. The driving performances based on the realised data of the month May varies in values for the on-time performance between 65% and 95% and a delayed performance between 80% and 99%. Most trains however had a 90-95% (on-time) and a 94-99% (delayed) value. As an assumption the values 93% for on-time trains and 98% for delayed trains are taken for simulation.

Dwell times are dependant per train type and station. For example, the Thalys receives a 200 second dwell-time at Schiphol. Intercities generally have a 60 second dwell time, with an exception on Schiphol where trains need 90 seconds because of all (inexperienced) passengers with large bags. The latter does not apply for trains ending on Schiphol, they also have a dwell time of 60 seconds at Schiphol. Sprinter trains have a general dwell time of 30 seconds at regular stations and 45 seconds at Schiphol. These values are extracted from the realised data with some rounding.

As these values have some inaccuracies, one should only use these as indication. The values should approximate the real values, but because of the comparing character of this research set-up it is assumed that flaws in these values will affect all DVM concepts equally and will therefore not influence this research significantly.

4.4.3 Flaws and work-arounds

Simulating in OpenTrack has its limitations. For several aspects of the simulation process work-arounds are needed and at some place even some flaws pop-up which have a limited effect on the reality of the model. They are described below.

Early trains

OpenTrack only allow for initial delays with a positive value, resulting in the inability to simulate early trains. Realised data shows that there are multiple train series with early trains. To cope with those, it is necessary to shift the entry times to an earlier time and adjust the delays accordingly to get the same result as the realised trains.

Cross-platform switch

The Cross-Platform switch cannot be directly modelled in OpenTrack. This is because of the fact that the dispatching rules are from the point of view of the train, not the infrastructure. The actual XPS just sends a train to the 'other' track as the preceding train for efficient use. In OpenTrack one gives a train a preferred track, and if that one is occupied it will choose the other one. As both tracks allow the same speeds and are about the same length, this doesn't influence the quality of the simulation. It actually functions more like the XPS-system at the Zürich Museumstrasse railway station: A preferred track with a back-up alternative.

First come first served

The first come first served algorithm is also executed from an infrastructure point of view, which OpenTrack is not fully capable of. FCFS is actually programmable in the software, but the trigger-point needs to be determined in an amount of seconds 'look-ahead time'. OpenTrack always tries to dispatch in such a way that trains can drive through green signals without a need for braking. This means the look-ahead distance is already just over two blocks, just as in today's situation. The look-ahead time is therefore assumed to be zero.

Common cause in delays

Simulating with stochastic variables has large possibilities, but also some limitations. As initial delays in this model have their causes per definition outside the model, they have a quasi-unknown cause. In reality multiple trains might get delayed consecutively by the same cause, but OpenTrack does not allow to 'bundle' delayed trains. The used realised initial delay distributions are therefore still correct within the model, but there are slight changes in the interactions between certain trains. Where normally train orders do not change too often, it is more likely to happen in the simulations. In a densely used network the operations therefore seem to be more perturbed than it actually is. To avoid this, one could simulate by using specified delay scenario's. This is very time consuming and could cause lack of objectivity by the selection of scenarios.

Driving performance

The performance of trains varies over location, and train series. For the purpose of validation it is set per train series. The inhomogeneity of the driving causes problems in the validation as it results in worse quality as one measures further in the model. Which is a logical result in modelling. Based on the outcomes of the driving performance these values are averaged over the train types for use in further simulation.

4.5 Summary and conclusion

Simulating in OpenTrack allows realistic reproduction of train operations. It requires infrastructure data input, in this case provided by ProRail. This data is not 100% correct and also the conversion contains some mistakes which are corrected with the help of video material (YouTube[2]). A hypothetical timetable based on expected frequencies will be used as one of the main inputs. Although the chance is big that this won't be the utilised timetable, it is still realistic for these simulations, because of the relative comparisons in this research with one single timetable. The performance indicators used in the model are the delay (per train), the maximum delay of a single train and the percentage of the Cross-Platform Transfers maintained. All rescheduling elements are modelled and simulated in different combinations.

[2]https://www.youtube.com/watch?v=CXVxD5q9u7c

Before the simulation the validation of the model is executed, which is done within certain margins as an exact match seemed impossible due to the amount of stochastic events in reality.

Chapter 5

Results

5.1 Output

The model can generate a lot of data, as can be specified by the user of the software. There are several possibilities when trying to retrieve the right data. It can be done with virtual measuring instruments, by analysing track occupations, with graphical outputs, or by just using the delays at the railway stations. The latter is used for this case as this is also the way the real-world data is retrieved. For every alternative 30 runs of 3:10 hours are performed, which generate a lot of data. To analyse this data several options - software packages - are available. The most convenient one is Matlab, which is capable of handling very large datasets. The data analysed consists of over 2600 trains having multiple stops to be analysed, generating datasets which aren't convenient for analysing by hand.

Performance indicators

A short recap of the used indicators is given in this section. The delay of an individual train is measured by its delay at the last point in the model (Hoofddorp) minus the delay it had in the delay-free scenario. This is done to eliminate the potentially poor scheduling design for the schedule used in the simulations. The initial delays are not corrected for, as they are identical for all alternatives and the results are better to compare to reality.

The maximum delay describes the train in the 30 runs with the largest amount of delay. This is a typical outlier and included, trying to show the worst case scenario. Besides that, also the percentage of Cross-Platform-Transfers kept is analysed for a maximum of 3 minutes waiting time. This aspect is analysed further on.

5.2 Prioritisation

Reordering is the first aspect tested because this aspect is used in all scenarios. Therefore the prioritisation is first analysed, because the most promising aspects are used for further testing in the other concepts. The tested Prioritisations are FCFS, train type, biggest delay and the destination of the train.

5.2.1 Overall results

The main indicators coming out of the runs are displayed in table 5.1 and show some interesting outcomes. The average delays caused within the model are between 85 and 95 seconds. This leads to two presumptions: the prioritisation doesn't make that much of difference and the interactions between (delayed) trains around Schiphol seem to cause an additional delay of around 90 seconds.

Table 5.1: Results of simulating with the different basic prioritisations. Sorted by average delay.

Prioritisation	Average delay [s/train]	Max. delay [s]	XPT connections kept [%]
Biggest Delay	85.7	1004	78.6
FCFS	87.3	1184	80.3
Destination	90.9	1132	78.3
Train Type	94.8	1132	76.1

The table shows that the prioritisation used today is the second best of these four based on the average delay, and the best based on the cross-platform transfers kept. The best variant can be found in prioritising by biggest delay based on the average delay. Which could sound as a logical outcome, but this doesn't necessarily has to be this way. Letting the most delayed train go first might prevent the growth of the delay, but could cause an equally large delay (as the prevented one) to another train. The result however shows that this is - solely looking to these forms of prioritisation in this case - the best form of prioritising.

It is very tempting to compare these outcomes to today's situation, but this would be a non-realistic comparison. The reason for that can be found in the differences in the schedule design, the amount of trains running per hour and the earlier mentioned differences in the occurrence of the delays. On the contrary the results of the simulations are very comparable as all these parameters are the same for all variants. To understand the results a bit better, it is valuable to dive a bit deeper in the results.

5.2.2 Further analysis

The graph illustrated in figure 5.1 - with the corresponding values showed in table 5.2 - shows that not only the values for the average delay are very comparable, but that also the bandwidth of the distributions are very similar. All distribution show that between the second and third decile the outcome is 0. These are the trains driving through the model as they did in the run without any delays, which was an approximation of a conflict free schedule. Also interesting are the trains being able to gain a negative delay compared to the delay-free run. This is either a result of poor scheduling in the first place and being able to drive without any interaction with another train or just delayed train that can catch up a little by driving slightly faster and the fact that they only need their minimum dwell time at the station.

Table 5.2: Results of simulating with the different prioritisations. The 10th till the 90th refer to the percentiles with delays in minutes.

Rescheduling elements	Average delay [s]	10th [min]	20th [min]	30th [min]	40th [min]	50th [min]	60th [min]	70th [min]	80th [min]	90th [min]
Biggest Delay	85.7	-0.2	0.0	0.0	0.2	0.5	0.9	1.4	2.5	5.2
FCFS	87.3	-0.1	0.0	0.0	0.2	0.5	0.9	1.4	2.4	6.5
Destination	90.9	0.0	0.0	0.0	0.2	0.5	0.9	1.4	2.6	5.6
Train Type	94.8	-1.1	0.0	0.0	0.1	0.5	1.0	1.7	3.5	7.0

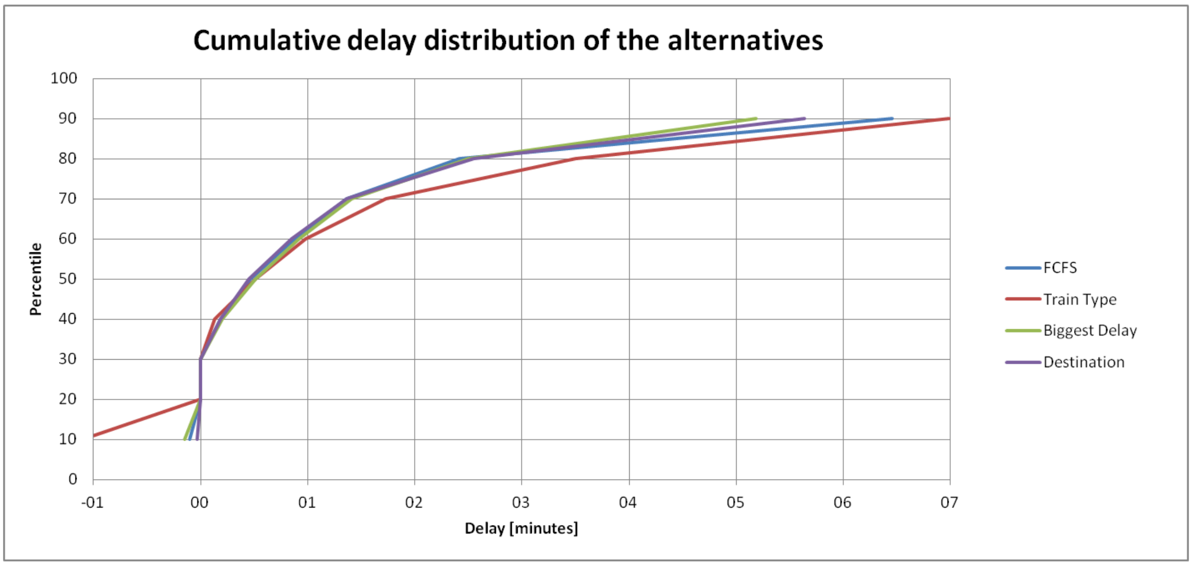


Figure 5.1: Cumulative delay distributions for the four prioritisations tested in OpenTrack.

Figure 5.1 and the corresponding table only give an overview of all the trains together. Two of the prioritisations however prioritise by fixed properties of a train, namely by train type and by destination of a train. It is therefore interesting to obtain a look inside the delay distributions of the train types and destination-wise prioritisations.

Train type & Destination

The prioritisation by train type and by destination are both based on a certain hierarchy where either the 'faster' trains or the trains with the furthest destination have priority over lower ranks. In case of equality the trains are handled by first come first served. When looking deeper in the data by analysing specific train types or trains with specific destinations - where one would expect differentiations in this category - one sees some remarkable outcomes. The trains higher in the the hierarchy (the long-distance or the high-speed trains) barely have any profit of these kind of prioritisations. But the lower ranked trains do suffer from hindrance from the other trains. The net effect therefore is a negative one. The prioritisation by train type is one of the worst ones, as all train types are experiencing larger delays as in for example the FCFS. Prioritising by destination does however creates a small benefit for one group of trains. These are the non-highspeed trains, heading for Leiden and Den haag. More detailed results of the prioritisation by destination can be found in appendix E.

Cross-Platform Transfer

As table 5.1 shows, the XPT connections kept does not correspond to the average delay. The best performing DVM system - prioritising by biggest delay - is not keeping the most XPT connections. The number one rank in the the XPT connections is the FCFS algorhitm. This is explainable by an example. Assuming the two XPT trains forming a connection together are both on-time. Whether the connection will hold depends on interactions with other trains in the system. In case of the FCFS algorithm the XPT trains are likely to continue without interactions. In the case this happens with the biggest delay algorithm, one of the trains might get in conflict with a delayed train (following the connecting XPT train). In FCFS the XPT train could go first, in the latter case the train has to wait. In such scenarios connections might be broken. Although this is a specific case, from watching the simulations one can learn that this does happen and is likely to be causing the differences in the total amount of XPT connection being kept.

5.3 DVM Concepts

In the previous section both the FCFS algorithm and the biggest delay prioritisation scored relatively good. Therefore they are both used for further testing in combination with the other components of rescheduling. This means besides the 4 reordering algorithms also 6 combinations are simulated. The results are analysed per rescheduling element including comparison with the FCFS and biggest delay DVM.

5.3.1 Rerouting

When analysing the results of rerouting in combination with FCFS and the biggest delay algorithm one sees positive, but mixed results of the implementation of rerouting. As table 5.3 shows in both cases improvement is present, but in very different amounts. In case of the biggest delay algorithm roughly a 30% improvement on the average delay is measured in simulation. For the FCFS algorithm this amounts is only a meagre 2,3%. Also the impact on the amount of XPT connections kept is surprisingly different. The biggest delay prioritisation results in a larger amount of XPT connections kept, where the opposite is true for the FCFS algorithm.

In figure 5.2 the cumulative delay distribution of the rerouting alternatives is drawn. The differences between the FCFS and the FCFS-rerouting are barely visible. For the Biggest delay case it is clearly visible that the main difference is made in the top 50% of delayed trains. This means the trains encountering the most delay in the model are having an easier time passing through with rerouting possibilities.

Table 5.3: Rerouting results of the simulation, sorted by average delay.

Rescheduling elements	Average delay [s/train]	Max. delay [s]	XPT connections kept [%]
Biggest Delay-Rerouting	60.2	692	79.4
FCFS-Rerouting	85.3	1531	76.9
Biggest Delay	85.7	1004	78.6
FCFS	87.3	1184	80.3

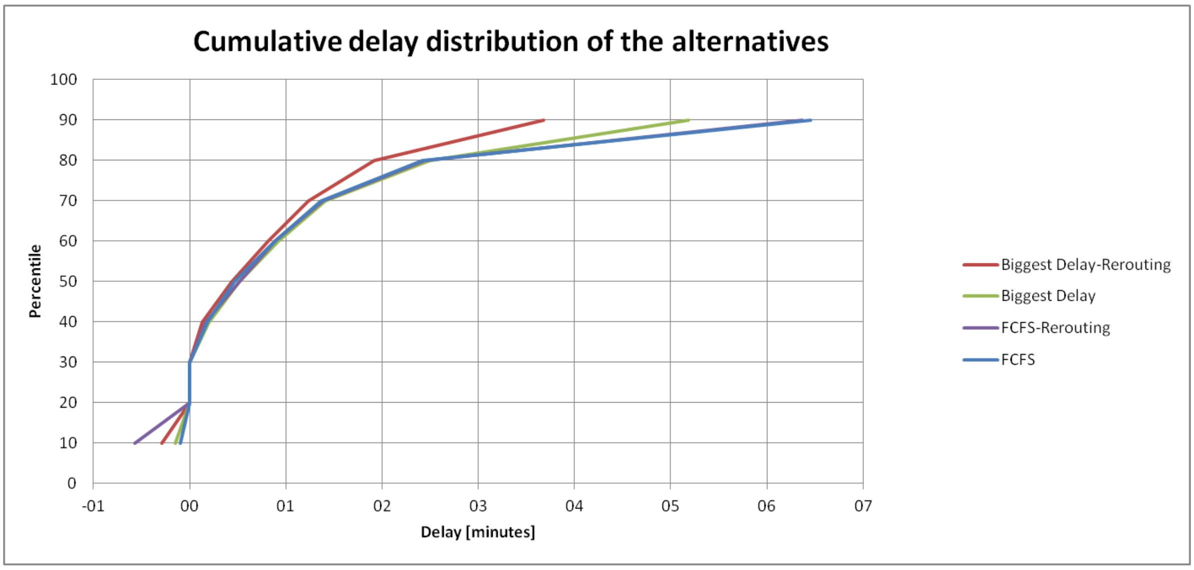


Figure 5.2: Cumulative delay distributions for the alternatives consisting of reordering and rerouting combined with the distributions of the two 'best' prioritisation algorithms.

5.3.2 Retiming

Also the results of the effects of retiming show mixed results (table 5.4). Again both improvements and decreases in performance are results of adding retiming as an element of a DVM system. For the biggest delay algorithm the retiming element causes an 18% improvement, where for the FCFS algorithm a 23% larger average delay is simulated. Remarkable is that for both alternatives the amount of XPT connection kept drops to a poor 69,4%. This shows that retiming has only positive effects with the right combinations in prioritisations and is not beneficial for the XPT connections.

Table 5.4: Retiming results of the simulation, sorted by average delay.

Rescheduling elements	Average delay [s/train]	Max. delay [s]	XPT connections kept [%]
Biggest Delay-Retiming	70.2	830	69.4
Biggest Delay	85.7	1004	78.6
FCFS	87.3	1184	80.3
FCFS-Retiming	107.7	1244	69.4

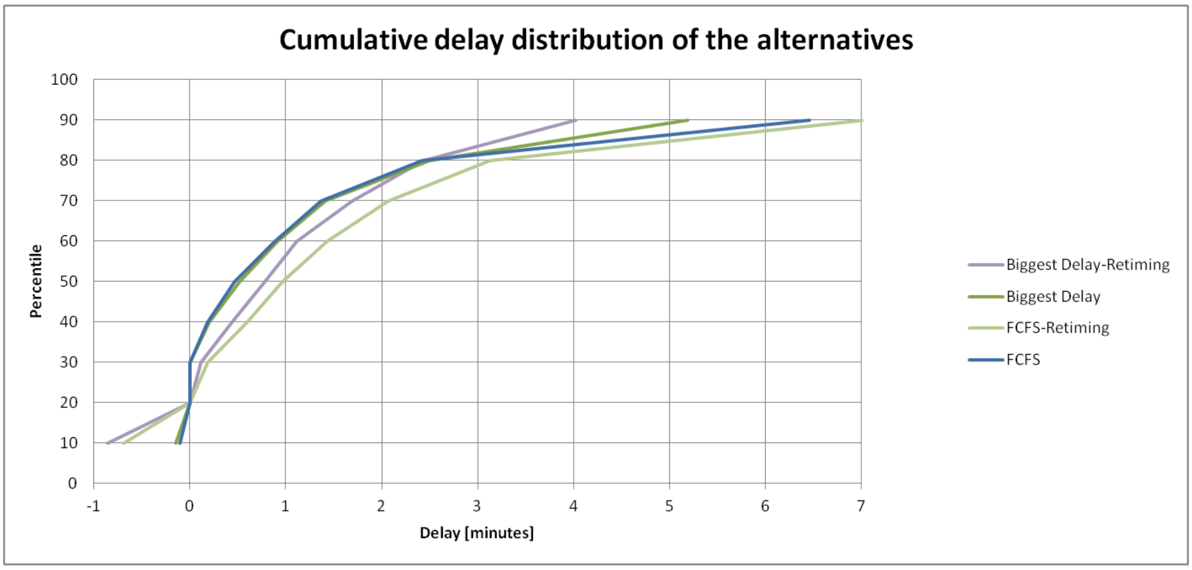


Figure 5.3: Cumulative delay distributions for the alternatives consisting of reordering and retiming combined with the distributions of the two 'best' prioritisation algorithms.

5.3.3 Reordering, rerouting and retiming combined

The final possibility - the combination of reordering, rerouting and retiming - is also tested as there are signals so far that this might be the best solution. Both retiming and rerouting gave an improvement to the biggest delay prioritisation. The effect of combining them is a slight negative one. In both cases an improvement is seen compared to the the case with solely reordering and retiming. But if one compares it with the reordering and rerouting combinations the results are slightly more negative. The reason for this, is that the rerouting allows for very efficient capacity use in perturbed situations, which is partially undone by the retiming measures as it steers on larger headways just before the bottleneck. The results are shown in table 5.5.

Table 5.5: Rerouting-retiming results of the simulation, sorted by average delay.

Rescheduling elements	Average delay [s/train]	Max. delay [s]	XPT connections kept [%]
Biggest Delay-Rerouting-Retiming	69.1	829	69.7
Biggest Delay	85.7	1004	78.6
FCFS	87.3	1184	80.3
FCFS-Rerouting-Retiming	102.5	1150	68.1

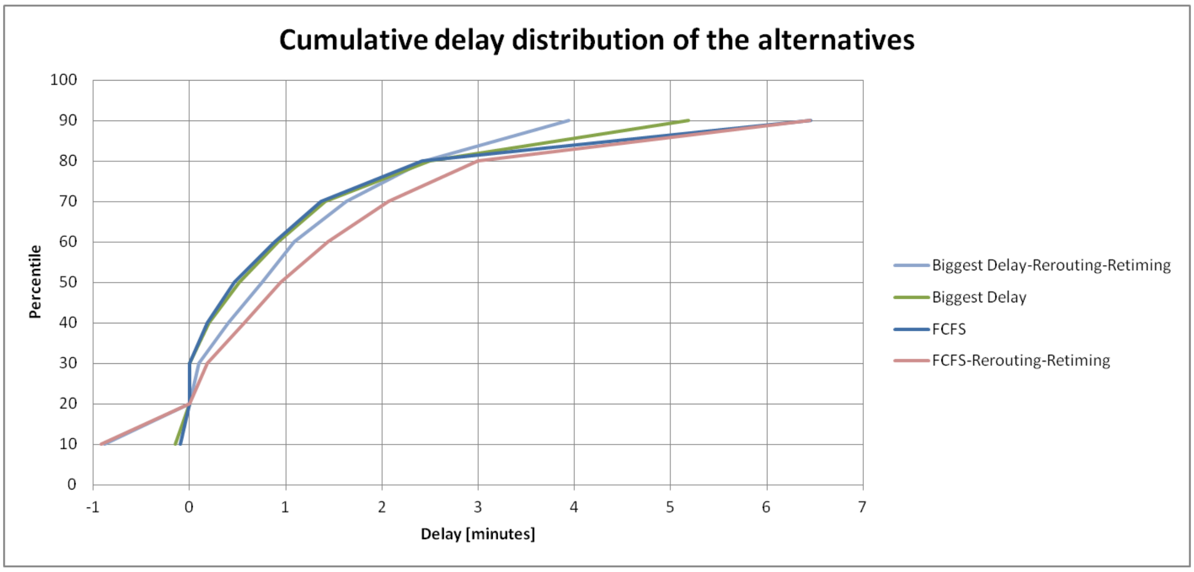


Figure 5.4: Cumulative delay distributions for the alternatives consisting of reordering, rerouting and retiming combined with the distributions of the two 'best' prioritisation algorithms.

5.3.4 Overview of the rescheduling elements

Recapping all the different options one gets a ranking based on average delay as is illustrated in table 5.6 and figure 5.5. The results show that it is not the best solution to add as many rescheduling elements as possible as some conflict with each other. The biggest delay prioritisation in combination with rerouting forms the most effective rescheduling for the Schiphol region according to these simulations. The complete results are found in appendix E.

Table 5.6: Overall results of the simulation, sorted by average delay.

Rescheduling elements	Average delay [s/train]	Max. delay [s]	XPT connections kept [%]
Biggest Delay-Rerouting	60.2	692	79.4
Biggest Delay-Rerouting-Retiming	69.1	829	69.7
Biggest Delay-Retiming	70.2	830	69.4
FCFS-Rerouting	85.3	1531	76.9
Biggest Delay	85.7	1004	78.6
FCFS	87.3	1184	80.3
Destination	90.9	1132	78.3
Train Type	94.8	1132	76.1
FCFS-Rerouting-Retiming	102.5	1150	68.1
FCFS-Retiming	107.7	1244	69.4

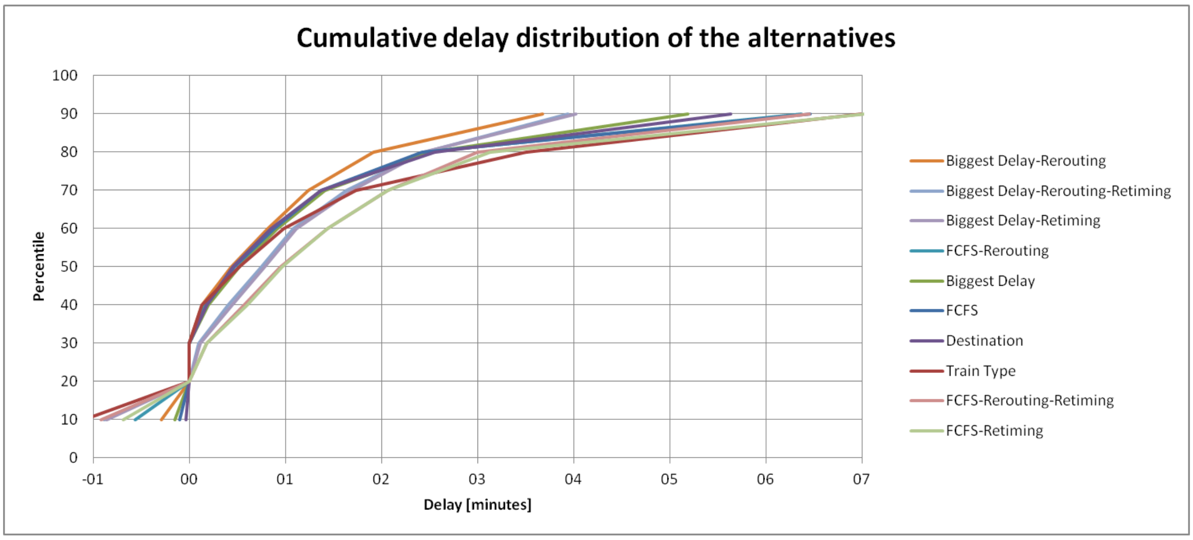


Figure 5.5: Cumulative delay distributions for all the alternatives.

5.4 XPT-Connection rate

For all alternatives a maximum of three minutes waiting time (in case of delay) is included in the cross-platform transfer. As this was an assumption based on personal experience it was interesting to look to the elasticity of this parameter. It is still assumed that 3 minutes is a minimum necessary time for a cross-platform transfer. For the best scoring set of rescheduling elements the elasticity is tested. It is done by running the exact same simulations with a four, five and six minute waiting time limit to see the effects.

The DVM-alternative 'biggest delay - rerouting' is used for these simulations as this one performed the best. One can imagine that when trains are waiting for each other within a bottleneck that delays will build up as well. The effects of this are illustrated in figure 5.6 and show the logical relation of the waiting time and the amount of cross-platform connections kept. The results are not very surprising but do show an estimation of the impact. The same graph also shows the decrease in delay which is also an understandable result of increasing the waiting time. The change however isn't really linear in the average delay. With every extra minute the effects gets more extreme causing complete instability of the system. From 7 minutes on, one sees extreme delays in the figure.

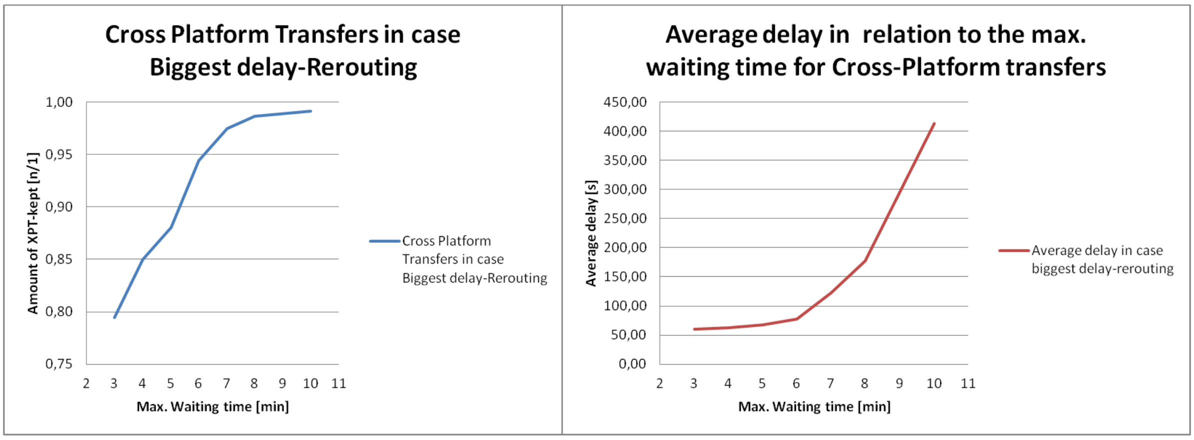


Figure 5.6: Showing the relation between the amount of XPT-connections kept and the XPT maximum waiting time (left) and the relation between the average delay caused in the system and the XPT maximum waiting time.

5.5 Conclusion

The different building-blocks of rescheduling - reordering, rerouting, and retiming - all have their benefits. The effects of the elements influence each other, not necessarily in a positive way. Observing solely the different ways of prioritisation, the biggest delay prioritisation and the FCFS algorithm score the best concerning the average delay en the XPT connections kept. Nevertheless the reordering by train type and destination are not scoring too bad either. With the addition of rerouting, differences get bigger and the biggest delay algorithm seems to be significantly better in all aspects. When solely adding retiming to the reordering, it has both negative as beneficial effects, depending on the way of reordering. Adding retiming as an building block to both rerouting and reordering, it generally results in a worsening performance. Purely observing the results of the simulation, biggest-delay prioritisation in combination with rerouting gives the best performance.

Chapter 6

Conclusion

6.1 Research questions and answers

6.1.1 Sub-questions

Developing and analysing feasible, improved DVM concepts for the station of Schiphol airport for the near feature, requires to answer the following research questions:

How does today's DVM works?

The DVM is an overlay of today's route-setting system which is capable of handling delayed trains (the normal automated route setter is not capable of doing this). It consists of the first come first served algorithm (FCFS) which allows the first train to go first in case of a route conflict. Besides that, it uses platform sides in a dynamic way utilizing the cross platform switch (XPS). This allows a train, heading for Schiphol and scheduled for platform 1-2 or 5-6, to use either side of the same platform dependant of which side the preceding train has used. Besides that the DVM doesn't allow a switch from the inner to the outer tracks and vice versa (keeping your lane principle). These functions are all intended to reduce conflicts to a minimum and allow trains to go through Schiphol as quickly as possible. Steering on throughput (what is done at Schiphol) works positive for the amount of trains one can handle, but not necessarily for the reliability of the timetable.

How will railway traffic and infrastructure lay-outs develop in the future around Schiphol?

The OV-Saal project, together with the integration of the high speed line in the main rail network, will change infrastructure and frequencies around Schiphol drastically. Infrastructure will be expanded - from double to quadruple tracks - between Riekerpolder and Duivendrecht and even further east. The Riekerpolder Aansluiting (junction ASRA) will be transformed to a full double fork construction, allowing trains to chose the right track without unnecessarily hindering other train paths. Impacting the DVM the most is the cross-platform transfer, which requires two trains to enter the station parallel and use both platform sides of the outer platform. This conflicts with both the XPS and the keeping your lane principle of today's DVM.

How does one measure the performance of a dynamic railway traffic management system?

To measure the performance of a dynamic railway traffic management system, one needs to measure the performance of the area wherein it operates. Within this area - in this case the area of the model - one can measure whether trains are leaving the model either more punctual or less punctual than they enter it. This gives an average delay value per train which is very comparable between different systems. Besides that, the maximum delay is taken into account to avoid averagely great systems with terrible outliers. As the future system has to cope with the cross platform transfer, it is also integrated into the performance of a DVM system. This is done by looking at the amount of connections kept with a certain waiting time threshold.

In what way can one prioritise trains?

One can prioritise trains based on almost all their characteristics or simply without any (first come first served). Not all prioritisation would make sense, therefore only a selected four were used in this research. Two of them are not variable in time thus fixed characteristics: the destination of the train and the train type (high speed, IC etc.). These allow long distance trains to go first in case of a conflict. The other two are the FCFS algorithm and the prioritisation based on the biggest delay of the train, which are both focussing on maximizing throughput in the first place.

Which dynamic railway traffic management systems are nowadays already used?

At the moment two systems are publicly documented. These are the systems in Schiphol (XPS & FCFS) and in Zürich Museumsstrasse (XPS). Both consist of the cross platform switch but have slightly different methods of executing these. At Schiphol trains are alternated between platforms 1-2 and 5-6. The system in Zürich sends trains to the inner tracks when possible, otherwise the outer tracks are used. The Schiphol system allows to handle delayed trains as well by simply prioritise trains with FCFS algorithm. In that way scheduled orders aren't necessarily maintained (reordering).

Which requirements of a dynamic railway traffic management system are requested by stakeholders?

Combining the requirements and wishes of all stakeholders, one comes to the following set of characteristics for a new DVM system: Safe system, capable of handling the timetable stably including the cross-platform transfer, fully automated and controllable. Besides that the system should allow to be understandable for traffic controller and thus simple. Preferably passenger should be able to be informed of platforms-side changes well in advance (5 min.).

What is the performance of today's dynamic railway traffic management system?

Most values of today's performance are used for validation purposes, but aren't available for comparison as the situation will be completely different. The cross-platform transfer and the higher frequencies for example are not implemented in today's DVM, causing a skewed comparison. For a fair comparison the elements of today's system, implemented in the new situation could be analysed. This would be the simulated variant with the FCFS (reordering) and the rerouting building block. Implemented in this variant is the cross-platform connection with a 3 minute waiting time. Values of the performance indicators for this situation are: an average delay of 85,3 seconds and a XPT-rate of 76,9%.

What dynamic railway traffic management system strategy performs best in the future situation?

This is depending on which performance indicators are considered the most important. Solely looking at the average delay per train the combination of reordering by biggest delay in combination with rerouting performs the best. This combination also has the second highest performance concerning the amount of XPT connection kept. Is solely the latter the most important, than the FCFS algorithm - without any other elements - is the best solution.

What is the improvement relative to the old dynamic railway traffic management system?

As mentioned earlier, both are not really comparable, as the infrastructure and the service pattern are completely going to change. The FCFS in combination with the rerouting (which is similar to today's system) applied to the future, can be compared. In table 6.1 the comparison is made. It shows that today's system scores on all 3 performance indicators less than the 'biggest delay - rerouting' alternative.

Table 6.1: Today's DVM concept compared to the best solution

Rescheduling elements	Average delay [s/train]	Max. delay [s]	XPT connections kept [%]
Biggest Delay-Rerouting	60.2	692	79.4
FCFS-Rerouting	85.3	1531	76.9

6.1.2 Main question

What DVM concept utilises the capacity of Schiphol airport railway station and surroundings the most efficient for the infrastructure lay-out and timetable of the near future?

When introducing the cross-platform transfer in combination with the infrastructure and timetable changes for the near future it is recommended to keep using a dynamic railway traffic management system. It has proven to be a good alternative for manual dispatching and especially when traffic is becoming more complicated and dense it is wise not having to rely on human capabilities. It is recommended to use a prioritisation algorithm according to the biggest delay principle. In combination with dynamic routing (or rerouting) it assures an high performance system concerning throughput. This is based on the outcomes of the simulations when looking at the performance indicators. In case the biggest delay algorithms is considered undesirable by for example ProRail, the seconds best alternative is the first come first served algorithm. When using that system one ends up with today's system with the main differences being the cross-platform transfer support and the rerouting which is dependant on the train and not solely on the planned track usage.

Concerning the cross-platform transfer connection it is recommended to keep waiting times as low as possible. This is beneficial for the throughput at the Schiphol airport railway station. This research shows that it is actually possible to execute a cross-platform transfer connection while dealing with very high frequencies, without the system getting unstable.

6.2 Further research

Because of the limitations of the software and the limited research time only certain aspects have been researched. Besides that the research has triggered some questions too, which are material for further research.

- This research is based on an experiment which is based on a very specific case. Would the results also be the same in more generic conditions? And is it therefore suitable at more locations in the Netherlands and abroad? These questions can be solved with a much more generic set-up and a very structural incremental expansion of conditions like the train frequencies. But afterwards it is then still questionable if that solutions holds for a specific case. This is material for future research.
- It is suggested to further research the effects of the cross-platform transfer connection and its alternatives. Especially in the future situation with higher frequency in the Schiphol area it is questionable if one should offer such a connection at such a vulnerable place. Therefore it seems wise to explore alternative options for the XPT, or the routing of trains around the Schiphol-area in general.
- With the upcoming developments in the implementation of ETCS in the Netherlands and the rest of Europe the potential of dynamic railway traffic management expands. Especially because of better and preciser location information and other communication tools one can steer trains more sophisticate through the network.
- Combining dynamic traffic management with real-time optimisation of the actual situation can create automated systems which are expected to operate in the future. Development in this area could maybe reduce lots of problems on the track.
- For the implementation of a form of retiming in a DVM system, some nifty systems might be needed to arrange this. The base for it - a good communication system - is on its way (ETCS). In retiming a lot of possibilities are available. It is interesting to find out which one would fit the best for a DVM concept.

- If simulation software would exist with far-going DVM possibilities it would be an alternative for OpenTrack. This could eliminate some work-arounds in this model and making this research even more accurate. The development of this software could give contributions to the future of DVM systems.

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Appendix A

List of most important abbreviations and terminology

The abbreviations and terms are ordered alphabetically.

Asra 'AmSterdam Riekerpolder Aansluiting', the major junction just east of Schiphol airport junction. Here the branches coming from Amsterdam Central and Amsterdam Zuid merge to continue in direction of Schiphol Airport.

DVM 'Dynamisch VerkeersManagement', Dutch for dynamic traffic management and the official name of the actual system at Schiphol.

FCFS 'First Comes First Served'. An algorithm for a DVM where the first train must go first.

InfraAtlas ProRail's infrastructure database with geo-data attached. The source for the simulation model.

NS 'Nederlandse Spoorwegen'. The Dutch national railway operator. Concessionaires of the main rail network in the Netherlands, connecting most cities in the country.

OpenTrack Swiss railway simulation software. Widespread used at academic institutes and rail consultants. Poorly used at railway operators.

Punctuality The amount of trains (percentage) being on-time within in a certain time margin. The margin is 5 minutes in Europe. For national use there is a 3 minute margin.

ProRail The Dutch national infrastructure manager who manages and maintains the tracks in the Netherlands. They are responsible for the signalling and interlockings and therefore also for the DVM system

XPS 'Cross-Platform Switch'. An algorithm for a DVM where both sides of a platform can be used by a train. The system should decide five minutes before arrival at Schiphol which platform side will be occupied by the train.

XPT 'Cross-Platform Transfer'. Two trains having a transfer relation in both ways handled on both sides of the same platform.

Appendix B

Formula's in OpenTrack

Strahl/Sauthoff (passenger trains)

For The calculation of the resistance one is dependant on multiple aspects of resistance as described in the formula's below. The largest aspect in resistance is the speed of the train and is always involved squared. The formula's are standard integrated within the OpenTrack software.

$$R = R_{LT} + R_{LP} + R_T + R_a + R_{Str}$$

R = Total Resistance [N]
R_{LT} = Locomotive rolling resistance (described below) [N]
R_{LP} = Passenger wagon rolling resistance (described below) [N]
R_T = Tunnel resistance [N]
R_a = Resistance due to the inertia of rotating objects [N]
R_{Str} = Distance resistance based on gradients, curves and switches [N]
The switch resistance is neglected in the simulation due to the minor influence on train operations.

Locomotive rolling resistance

$$R_{LT} = g \cdot \left\{ \left(f_l \frac{m}{1000} \right) + \left(k_{st1} \cdot [3,6 \cdot (v + \Delta v)]^2 \right) \right\}$$

g = Gravity [9,81 m^2]
m = Mass of Locomotive [kg]
v = Train speed [m/s]
Δv = Wind resistance [m/s]
f_L = Resistance factor [-]
k_{St1} = Resistance coefficent [kg $\cdot$ s^2/m^2]

Passenger wagon rolling resistance

$$R_{LP} = g \cdot \left\{ \left(1,9 \cdot \frac{m}{1000} \right) + \left(k_{Sa1} \cdot v \cdot 3,6 \cdot \frac{m}{1000} \right) + \left(k_{Sa2} \cdot [n + 2,7] \cdot [(v + \Delta v) \cdot 3,6]^2 \right) \right\}$$

g = Gravity [9,81 m^2]
m = Mass of Locomotive [kg]
v = Train speed [m/s]
Δv = Wind resistance [m/s]
f_L = Resistance factor [-]
k_{St1} = Resistance coefficent [kg $\cdot$ s^2/m^2]

Appendix C

Topology Schiphol Area

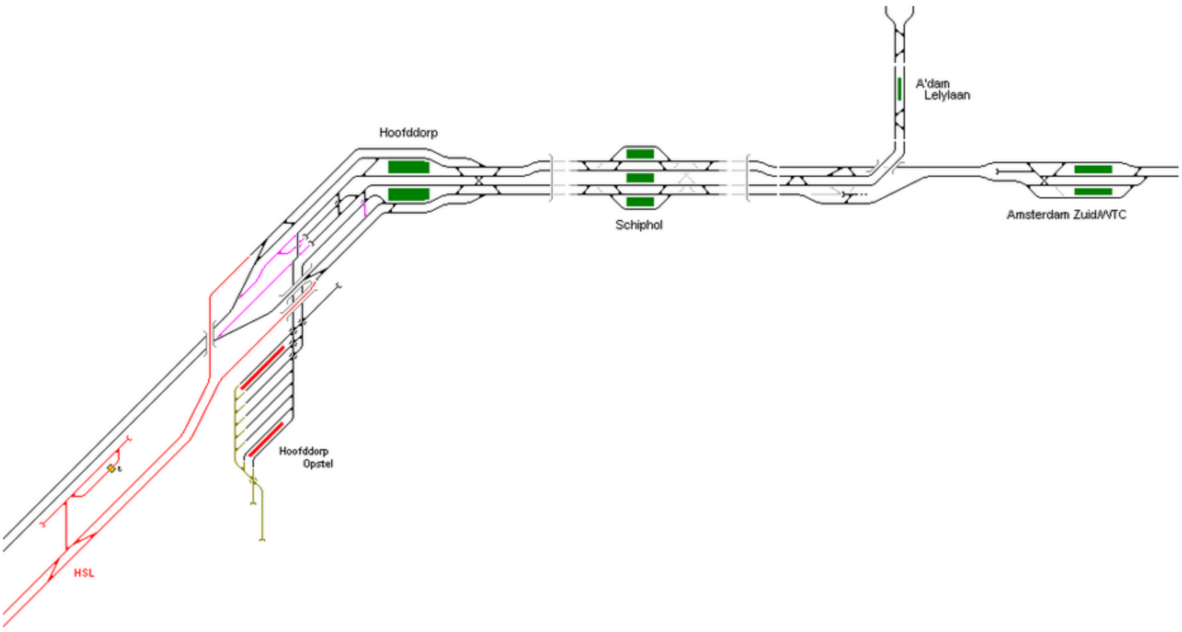


Figure C.1: Today's situation (Sporenplan.nl).

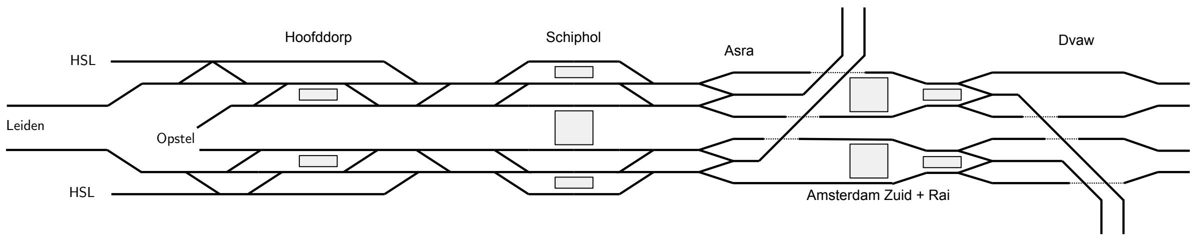


Figure C.2: 2018 situation.

Appendix D

Description of today's DVM system (Dutch)

D.1 Planprincipes huidig DVM systeem

Planprincipes DVM Schiphol

dd. 26 april 2012

Aanleiding

Sinds de dienstregeling 2007 wordt de treindienst in de flessenhals Schiphol (gebied van perronsporen Hfd t/m Asra) gestuurd volgens het DVM-principe, oftewel sturen op doorstroming. Voor de uitvoering heeft dit uiteraard consequenties, maar "sturen op doorstroming" stelt ook eisen aan het plan. Het plan moet zo worden ingericht dat

- de kans op onnodig oponthoud in de flessenhals minimaal is, en
- de doorstroomfuncties van Procesleiding goed kunnen werken (XPS=Cross Platform Switch; FCFS=First Come First Serve regelaar)

Dit wordt bereikt door een aantal basisprincipes in de planning te hanteren. Deze basisprincipes gelden voor alle treinen die van de flessenhals Schiphol gebruik willen maken.

Basisprincipes voor de planning (de 10 geboden):

1. Geen wisselend spoorgebruik in de tunnel: binnenspoor blijft op binnenspoor, buitenspoor blijft op buitenspoor. Doorwisselen kan bij Riekerpolder aansluiting.

2. Treinen van/naar HSL en Leiden rijden te Hoofddorp over de buitenste sporen; treinen van/naar Hoofddorp Opstel zoveel mogelijk over de binnensporen. Die treinen die van/naar Hoofddorp Opstel naar de buitensporen moeten om een goed evenwicht in treinaantallen op binnen- en buitensporen te krijgen, hebben herkomst/bestemming Zuidtak.

3. Speling op de rijtijd (standaard 5%) bij Schiphol afronden naar beneden. Let op: dit is afwijkend van het eerdere principe om zonder rijtijdspeling tot station Schiphol te plannen. Het betreft nieuw inzicht. Afronding rijtijdspeling naar beneden is niet anders dan bij andere stations/haltes die geen blokpunt zijn. Afronding naar beneden op Shl is belangrijk voor doorstroming. Hierdoor kan mogelijk negatieve rijtijdspeling tot Shl ontstaan.

4. Plan korte stationnementen om wachten op vertrek te voorkomen. Binnenlandse treinen maximaal 1 minuut, internationale treinen maximaal 2 minuten. Dit maximale stationnement van 1 resp. 2 minuten geldt ook voor eindigende treinen op Shl die leeg doorgaan naar Hfdo.

5. Alle treinen op de sporen 1/2 en 5/6 op Shl plannen met een A/V vanwege de XPS. De treinen op spoor 3 en 4 plannen met een korte stop, tenzij dat niet kan (bijv. vanwege omnummeren rangeerdeel van/naar Hfdo).

6. Op de binnensporen 3 en 4 rijwegen met 'Hoog Groen' plannen voor optimale doorstroming. Op de buitensporen 1/2 en 5/6 juist niet met 'Hoog Groen' plannen. Hier kan de XPS niet mee omgaan.

7. Het tekort aan stationnementstijd wordt na Shl, tot het volgende blokpunt, teruggegeven door 1 minuut extra speling in de rijtijd. Dit komt bovenop de normale 5% rijtijdspeling tussen blokpunten.

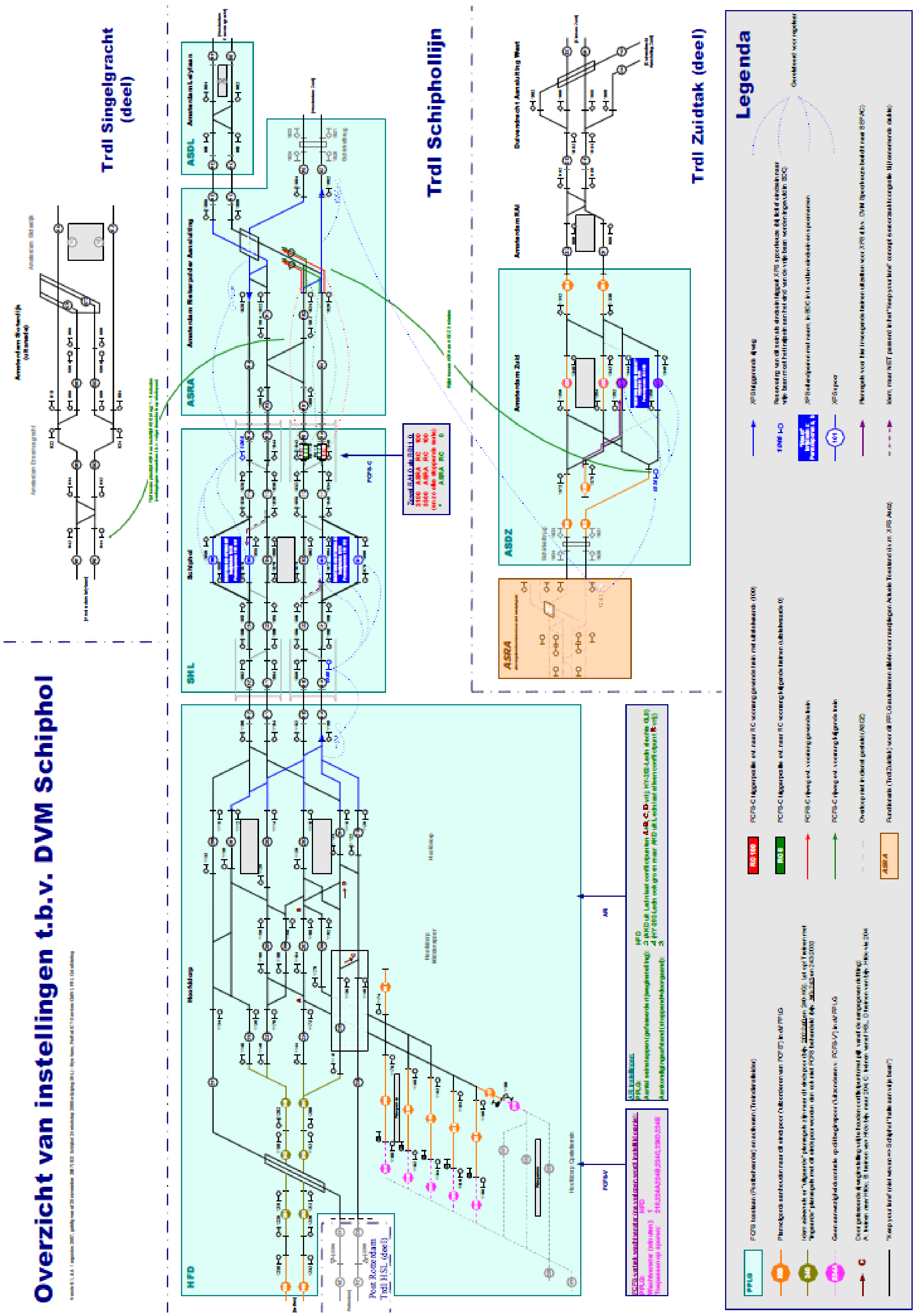
8. Hanteer opvolg- en overkruistijden van minimaal 2 minuten in de flessenhals Schiphol (perronsporen Hfd t/m Asra). Bij kortere opvolg- of overkruistijden krapte voor beide treinen compenseren door één minuut extra (rijtijd-)speling na Shl tot volgende blokpunt te plannen. Uitvoerbaarheid laten toetsen door VL/PAB. Voor perronopvolging geldt de standaard norm uit de netverklaring van 4 minuten.

9. Indien te Hoofddorp een A/V voor IC treinen van/naar Hfdo gepland is, dan IC ook omnummeren (bijv. 77XXXX). Procesleidingssysteem kan niet 2 aankomst- of vertrekregels van hetzelfde treinnummer binnen één pplg verwerken.

10. Om de doorstroming te bevorderen en wachten op vertrek te voorkomen kunnen op Shl geen cross platform of bewaakte (WRT) aansluitingen gepland worden.

Er worden geen specifieke TAD afspraken gemaakt voor de flessenhals Schiphol. Hoofddoel is sturen op doorstroming. Hier is Procesleiding op ingericht middels de doorstoomfuncties.

D.2 Instellingen huidig DVM systeem

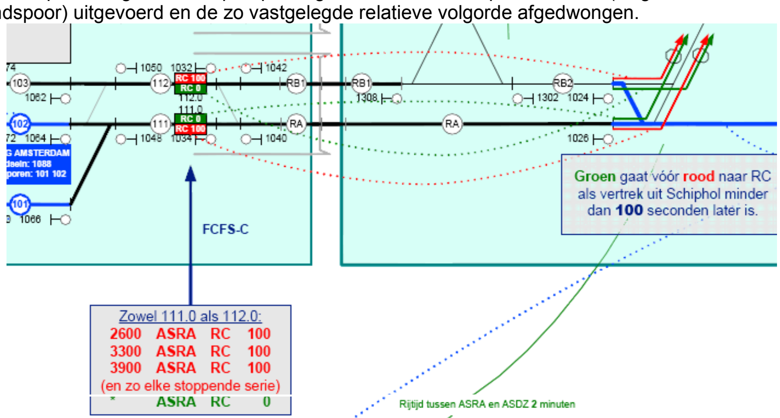


DVM Schiphol (24 treinen per uur per richting)

First Come First Served (FCFS)

Noodzaak	Sturen op doorstroming (afspraak: gelijkwaardige treinen)
Activeren	• Indien nodig ARI uitzetten voor ASDL, ASRA, HFD en SHL. • DVM -> FCFS instellingen -> aanvinken ASDL, ASRA, HFD, SHL.
Gevolg activeren	ARI aangezet voor alle planregels in betreffende PPLG's.
Terugkoppeling activering	• Indien dit de eerst geactiveerde DVM-regelaar is, wordt de DVM knop zeegroen ("regelaar actief"). • Betreffende PPLG's worden getoond als "ARI aan": alle planregels groen ("aan voor regelaar").
Niet van toepassing op	• Hoofddorp sporen KG, NG (naar Leiden) • Hoofddorp Opstelterrein (sporen 211-216, 221-223)
Beperkingen	• ARI ziet bij snelle treinopvolging alleen de voorste trein bij elk inrijsein. Aankondigingen werken daarom eigenlijk "First Seen First Served": een tweede trein die al voorbij het aankondigingspunt is, wordt pas behandeld als de eerste trein voorbij is. • Het venster van voor ARI uitgezette sporen kan momenteel niet worden gemanipuleerd bij geactiveerde FCFS. Het "uit" staan voor eindsporen wordt ongedaan gemaakt door het activeren van FCFS. Bij geactiveerde FCFS kunnen geen sporen worden uitgezet voor ARI. Workaround: planregels met dat eindspoor selecteren "uit" zetten voor ARI. Het "uit" staan voor beginsporen lijkt na activeren FCFS nog steeds het geval te zijn. Bij geactiveerde FCFS kan het "uit" staan voor beginsporen niet ongedaan worden gemaakt.
Aangekondigde rijwegen (FCFS-A)	
Volgorde planregels	Planregels worden ingesteld in volgorde van aankondiging, ongeacht de volgorde in het planvenster.
Gefaseerde rijweginstelling	Bij instelling van extra rijwegen is het moment bepalend waarop ARI concludeert dat één of meer extra enkelvoudige rijweg(en) moet(en) worden ingesteld.
Tijdelijk niet-beschikbare conflictpunten	Gemeenschappelijke elementen (wissels) in een in te stellen enkelvoudige rijweg worden in FCFS volgorde binnen ARI "gereserveerd" als de rijweg nog niet kan worden ingesteld. Een later getriggerde instelling van een enkelvoudige rijweg voor een andere trein die intussen wel mogelijk is, vindt niet plaats. Dit afdwingen van de FCFS volgorde wordt echter beperkt tot 10 seconden na het "reserveren". In die tijd moet een voor tijdelijke niet-beschikbaarheid zorgende trein de rijweg kunnen hebben vrijgereden, dus het aflopen van die tijd duidt op een probleem dat het voor langere tijd onmogelijk maakt de "gereserveerde" rijweg in te stellen. Daarom gaat de wel mogelijke rijweg alsnog vóór de "gereserveerde" rijweg.
Vertragingen verwerken	Niet nodig, ook planregels buiten het tijdvenster worden ingesteld. Indien voor overzicht in planvensters gewenst, mag er wel vertraging verwerkt worden.
Pas op!	Mengen van A+V (of gesplitste D / K) activiteiten met D / K activiteiten waarvoor rijweginstelling bij aankondiging plaatsvindt tot voorbij het conflictpunt geeft onevenredige bevoordeling van de D / K activiteit.
Aankomstafhankelijke Vertrekrijwegen (FCFS-V)	
Noodzaak	Voorkomen dat "late" treinen die nog moeten stoppen en halteren eerder de vertrekrijweg krijgen dan te vroege treinen die op het vertrek (insteltijd) wachten.
Triggering	Insteltijd moet zijn aangebroken EN de trein moet op het vertrekspoor aanwezig zijn: • Insteltijd aangebroken. • Treinnummer bij vertreksein. • Sectie voor vertreksein bezet.
Bedoeld voor	• Schiphol • Hoofddorp richting Schiphol
Niet van toepassing op	• Niet-gedetecteerde sporen Hoofddorp Opstelterrein (221A, 222A, 223A, 224A-224E)
Pas op!	Bij splitsing van activiteiten worden tweede en latere delen pas ingesteld als de trein bijna tot stilstand is gekomen.
Correctie (FCFS-C) naar Westelijke Tak (spoor RC naar Asdl)	
Noodzaak	Voorkomen dat aan de WT stoppende treinen door FCFS vlak voor doorgaande treinen de WT op worden gestuurd (daarmee ±4 minuten vertraging oplopend).
Maakt gebruik van	Machinist van stoppende trein kan gedurende ±2 minuten niet aan de seinen zien dat zijn rijweg over ASRA nog niet is ingesteld en blijft dus normaal rijden.
Gedrag	Doorgaande treinen krijgen voorrang als ze minder dan 100 seconden na de stoppende trein uit Schiphol vertrekken. Alléén in dat geval krijgt de stoppende trein enige vertraging.

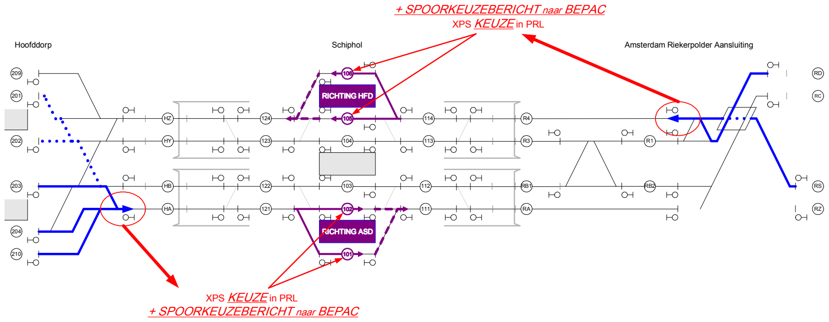
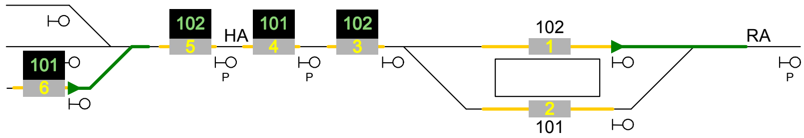
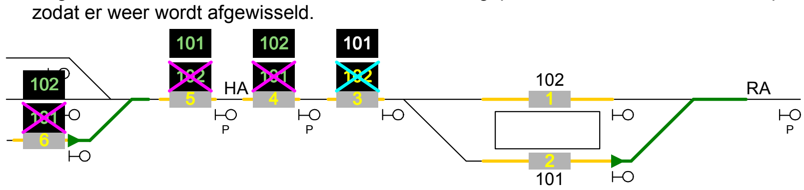
<table>
<tr><th colspan="2">DVM Schiphol (24 treinen per uur per richting)</th></tr>
<tr><td>Werking</td><td>Bij vertrek uit Schiphol wordt in de insteltijd van de planregel in ASRA de tijd van dat moment + een correctiewaarde gezet ("timestamp").
De correctiewaarde is 100 seconden voor de stoppende treinseries en 0 seconden voor alle andere treinen.
Alléén op aldus "getimestampte" planregels wordt de "eindspoorcontrole" (volgordecontrole naar eindspoor) uitgevoerd en de zo vastgelegde relatieve volgorde afgedwongen.

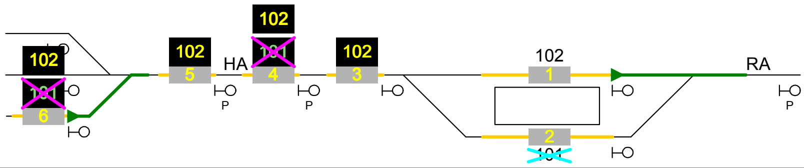


</td></tr>
<tr><td>Terugkoppeling werking</td><td>Insteltijd van de aangepaste planregel in ASRA wordt zeegroen getoond ("regelaar actief (geweest)").</td></tr>
<tr><td>Ingrijpen</td><td>Als de stoppende trein toch moet voorgaan, moet de planregel handmatig worden ingesteld.</td></tr>
</table>

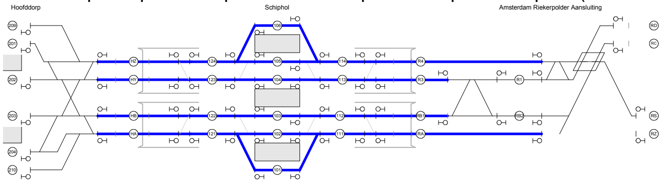
DVM Schiphol (24 treinen per uur per richting)

Cross-Platform Switch (XPS)

Reden	FCFS levert volgordewisselingen op die bij de beperkte perroncapaciteit van Schiphol direct leiden tot spoorwijzigingen.
Activeren	DVM -> XPS instellingen -> aanvinken RICHTING ASD en RICHTING HFD.
Terugkoppeling activering	• Indien nog nodig wordt DVM knop zeegroen (“regelaar actief”). • Aankomstsporen van aankomstactiviteiten worden getoond in groen (“aan voor regelaar”), óók als FCFS / ARI niet aan staat voor die planregel.
Keuzemoment	Rijweginstelling de tunnel in. • Keuze wordt naar BEPAC gecommuniceerd met een "spoorkeuzebericht". • RICHTING ASD: rijweginstelling in HFD naar spoor HA. • RICHTING HFD: rijweginstelling in ASRA naar spoor R4. 
Reden vroege keuze	• Eis NS: tenminste 5 minuten voor vertrek spoor bekend. • Rijweginstelling tunnel in is vroegste moment dat gekozen volgorde bekend is bij “keep your lane”.
Keuzemechanisme	Op het keuzemoment is het vrij zijn van perronsporen bij aankomst nog niet bekend => • Eerst triggerende trein na activeren: geplande spoor. • Volgende triggerende treinen: "dom" afwisselen ten opzichte van voorgaande trein. Als na elkaar de treinen 1 t/m 6 richting Amsterdam rijden, ontstaat de volgende situatie: 
Terugkoppeling keuze	Aankomstspoor in de aankomstactiviteit op SHL wordt zeegroen getoond (“regelaar actief (geweest)”).
Bijsturing: perronspoor van een trein afdwingen (“fixeren”)	• Planregel aankomstactiviteit selecteren. • DVM -> Planregel uit voor XPS. • Eindspoor in aankomstactiviteit wordt wit getoond. • Als dit wordt gedaan bij een reeds behandelde (onderweg zijnde trein), dan worden de erop volgende reeds behandelde treinen automatisch omgepland naar telkens het andere spoor zodat er weer wordt afgewisseld. 
Bijsturing: Eilandperronspoor niet bruikbaar (bv. 101)	Na evt. veiligheidsmaatregelen het spoor voor XPS blokkeren ("deze mag je niet kiezen"): DVM -> XPS instellingen -> uitvinken van Spoor 101 achter RICHTING ASD.
Gevolg van blokkeren	• Alle treinen waarvoor XPS al heeft gekozen voor het geblokkeerde spoor (101) worden automatisch omgepland naar het niet-geblokkeerde spoor (102).

DVM Schiphol (24 treinen per uur per richting)	
	• Voor elke omgeplande trein wordt weer een spoorkeuzebericht naar BEPAC gestuurd. In principe zijn dit spoorwijzigingen omdat de keuze al gecommuniceerd zou kunnen zijn. 
Terugkoppeling van het geblokkeerd zijn	Alleen via het DVM menu en kleur van door XPS gekozen aankomstsporen, geen directe terugkoppeling (spoornamen 101, 102, 105 en 106 zijn statische teksten).
Gedrag tijdens blokkering	• XPS maakt alleen keuze uit niet-geblokkeerde sporen. • Eindsporen in aankomstactiviteiten worden geel getoond om aan te geven dat de keuze voor XPS-regelaar beperkt was. • Als beide sporen geblokkeerd zijn, kiest XPS niets en worden de eindsporen wit (in dit geval ligt het meer voor de hand XPS de deactiveren voor het eilandperron).
Deblokkeren	• DVM -> XPS instellingen -> aanvinken van Spoor 101 achter RICHTING ASD. • De tijdens blokkering gekozen sporen van nog onderweg zijnde treinen worden niet automatisch gewijzigd omdat de keuze al gecommuniceerd zou kunnen zijn. Het wordt aan het oordeel van de treindienstleider i.s.m. de omroeper overgelaten of deze treinen direct weer afwisselend gebruik moeten maken van de beide zijden van het eilandperron. In dat geval: Aankomstplanregels van treinen die naar voorheen geblokkeerde spoor moeten gaan "uit" zetten voor XPS. Aankomst- en vertrekactiviteit voor de treinen m.b.v. mutatievenster omplannen. • De eerstvolgende keuze die XPS zal maken, wordt weer afwisselend ten opzichte van de laatst behandelde trein. Let op bij het handmatig omplannen van die laatst behandelde trein dat de keuze niet net gemaakt wordt tegen het nog niet omgeplande spoor (waardoor er twee treinen achter elkaar naar hetzelfde spoor worden gepland).
Deactiveren XPS (evt. voor één eilandperron)	DVM -> XPS instellingen -> uitvinken RICHTING ASD en (of) RICHTING HFD.
Terugkoppeling deactiveren	Eindsporen van aankomstactiviteiten worden wit getoond. Dit is ook het geval ook voor alle aankomstactiviteiten als FCFS (al) aan staat maar XPS (nog) niet geactiveerd is.

DVM Schiphol (24 treinen per uur per richting)

“Keep your lane”	
Reden	Maximale doorstroming door niet twee bottlenecks (capaciteit tunnelspoor en perroncapaciteit) aan elkaar te koppelen
Uitvoering	Niet “weven” voor/na Schiphol bij onverstoorde situatie: Voor Schiphol op binnenspoor => na Schiphol ook op binnenspoor (idem voor buitenspoor). 
Verstoring: perronspoor 103 of 104 versperd	Één perronspoor per tunnelspoor gebruiken: • Eilandperronspoor 102 c.q. 105 blokkeren voor XPS. • D.m.v. Routering gelijkelijk verdelen van (niet opgeheven) treinen over tunnelsporen. • Over het binnenspoor rijdende treinen in Schiphol laten halteren op spoor 102 c.q. 105.
Verstoring: tunnelspoor HY, HB, R3 of RB1 versperd	D.m.v. Routering het andere tunnelspoor voor alle (niet opgeheven) treinen gebruiken. • HB versperd: alle erover geplande treinen tot spoor 122 over spoor HA leiden. • RB1 versperd: alle erover geplande treinen na spoor 112 over spoor RA leiden. • HY versperd: alle erover geplande treinen vanaf spoor 123 over spoor HZ leiden. • R3 versperd: alle erover geplande treinen tot spoor 113 over spoor R4 leiden.
Verstoring: tunnelspoor RA of HZ versperd	D.m.v. Routering het andere tunnelspoor voor alle (niet opgeheven) treinen gebruiken. • RA versperd: Spoor 101 blokkeren voor XPS. Alle over RA geplande treinen vanaf spoor 121 over sporen 102, 112 en RB1 leiden. Door niet deactiveren van XPS gewoon spoorkeuzebericht naar BEPAC. • HZ versperd: Spoor 106 blokkeren voor XPS. Alle over HZ geplande treinen vanaf spoor 113 over sporen 105, 123 en HY leiden. Door niet deactiveren van XPS gewoon spoorkeuzebericht naar BEPAC.
Verstoring: tunnelspoor HA of R4 versperd	D.m.v. Routering het andere tunnelspoor voor alle (niet opgeheven) treinen gebruiken,. • XPS wordt niet meer gebruikt => BEPAC moet niet op spoorkeuzeberichten wachten (uit DVM stand). XPS hoeft echter niet te worden gedeactiveerd. • HA versperd: alle over HA geplande treinen tot spoor 111 over sporen HB, 122 en 102 leiden (geen enkele trein triggert nog XPS). • R4 versperd: Alle over R4 geplande treinen tot spoor 124 over sporen R3, 113 en 105 leiden (geen enkele trein triggert nog XPS).

DVM Schiphol (24 treinen per uur per richting)

Routering

Reden	Noodzaak tot bulkwijzigingen over alle betrokken PPLG's bij versperring van één tunnelspoor (baanvakoriëntatie).
Activeren	Knop Routeer in mutatievenster.
Start met Treinserie	Herrouteren van treinen uit één treinserie tussen gelijke in- en uitgang. • Start routering met knop "Treinserie". • Vul de treinserie in. Serie (veelvoud van 100). Even / oneven (= richting bij normale Nederlandse treinseries). Bereik (deel treinserie bij even/oneven; richting bij Belgisch genummerde treinseries). Enkel treinnummer: in het Van veld. Voor deze mogelijkheid bestaat de "shortcut" om vóór het aanroepen van de Routering (met de knop Routeer in mutatievenster) een planregel van één trein te selecteren. • Routeringscherm toont routering van de eerste kwalificerende trein.
Start met Oude routering	Treinen met dezelfde routering op een deel van het baanvak Hfd - Asra. Ook de relevante keuze voor treinen uit dezelfde treinserie waarvan de routering anders eindigt of begint op Hfdo! • Vul het interval in. • Kies met de spoorknoppen het te veranderen deel van de routering vanaf het laatste ongewijzigd te houden spoor tot en met het eerste ongewijzigd te houden spoor. • Geef aan dat het aangeven van de te wijzigen routering klaar is door op de knop "Nieuwe routering" te klikken.
Tijdinterval	• Standaardwaarden: van 5min na "nu" tot 20 min na "nu". • Maximumwaarden: van een uur geleden tot 3½ uur in de toekomst, eindtijd minder dan 24 uur na begintijd. • Als de eindtijd vóór de begintijd ligt (rond middernacht), wordt daar een dag later voor gebruikt.
Selectielijst treinen	• Geeft alle treinen die voldoen aan de gegeven criteria (serie, interval, oude routering). • (De)selecteren van (on)gewenste treinen: linker muisknop. • Tonen van de oude routering van een individuele trein: rechter muisknop op het treinnummer.
Kleuren selectielijst treinen	• Groen: trein is momenteel geslecteerd voor herroutering. • Wit: trein is momenteel geselecteerd voor herroutering, maar voldoet (nog) wel aan oude routering. • Rood: trein is niet (meer) te kiezen omdat deze niet (meer) voldoet aan de oude routering. • Geel: trein waarvan de oude routering wordt getoond – te kiezen d.m.v. de rechter muisknop op het treinnummer.
Verdere interactie	• Klik op de spoorknoppen voor het te wijzigen deel van de routering totdat de bestaande routering weer bereikt is. • Als Routering constateert dat het zelfstandig de nieuwe routering kan aanvullen, wordt de overeenkomstige knop actief. • Als Routering constateert dat de oude routering bereikt is, worden de knoppen "Voer in" en "Mutatievenster" actief.
Knop Mutatievenster	• Door Routering gewijzigde planregels voor alle PPLG's worden in het mutatievenster geplaatst. • Andere wijzigingen kunnen nu worden doorgevoerd, zoals infradwangen (voor het overzicht en gezien het doel werkt Routering alleen met sporen, zonder mogelijkheid om te kiezen tussen verschillende routes in een enkelvoudige rijweg).
Knop Voer in	• Gewijzigde planregels worden ook in het mutatievenster geplaatst, maar direct daarna in het plan verwerkt alsof er gekozen is voor Voer in plan. • Voor / tijdens Routering in het mutatievenster staande planregels worden ongemoeid gelaten. • Standaard controles tijdens invoeren van gemuteerde planregels worden uitgevoerd. • Bij afwezigheid van fouten in door Routering gewijzigde planregels is er in het mutatievenster dus niets veranderd na verdwijnen van Routeringvenster.

Appendix E

Results of the simulations

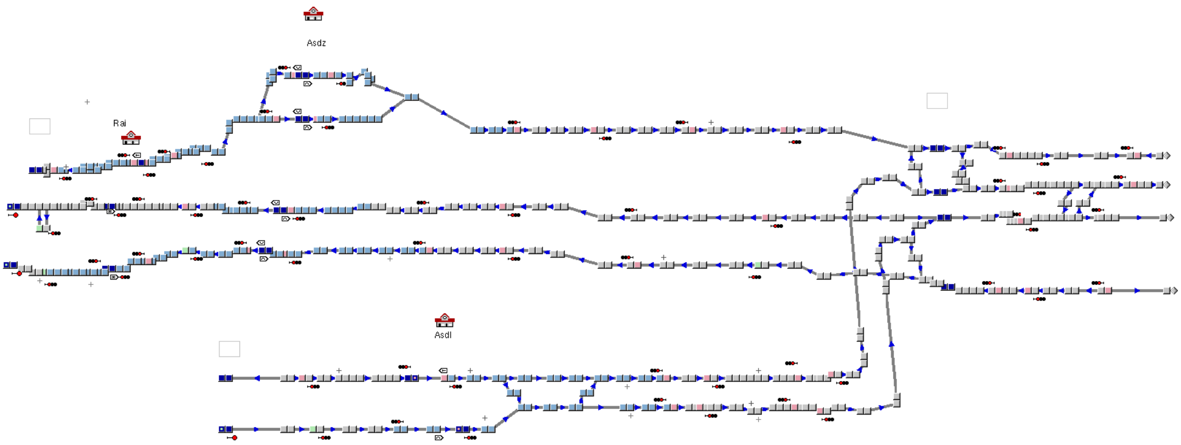
E.1 Overview

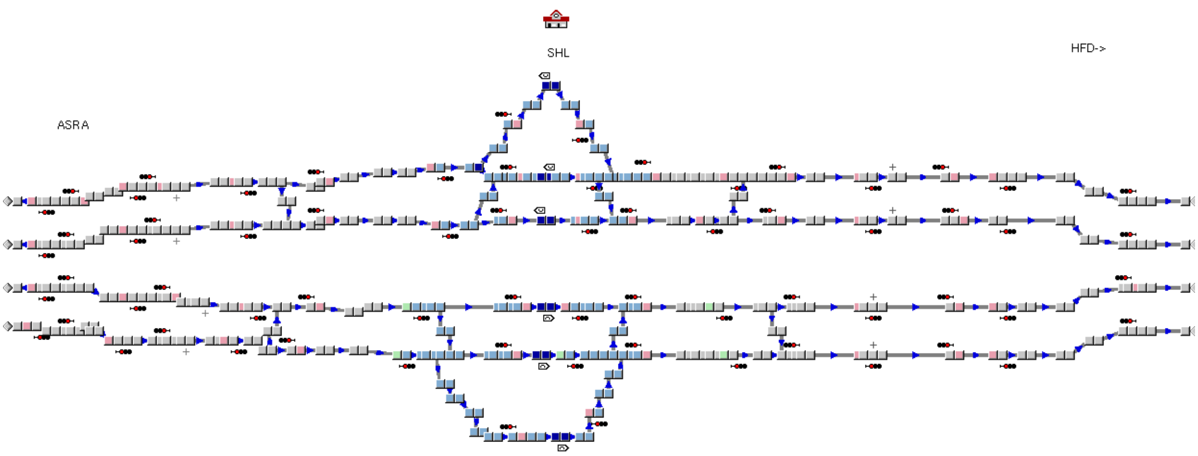
DVM Concept	XPT rate	Av. delay [s]	Max delay [s]	10th	20th	30th	40th	50th	60th	70th	80th	90th
FCFS	0.80	87.33	1184	-0.1	0.0	0.0	0.2	0.5	0.9	1.4	2.4	6.5
Train Type	0.76	94.80	1132	-1.1	0.0	0.0	0.1	0.5	1.0	1.7	3.5	7.0
Biggest Delay	0.79	85.65	1004	-0.2	0.0	0.0	0.2	0.5	0.9	1.4	2.5	5.2
Destination	0.78	90.87	1132	0.0	0.0	0.0	0.2	0.5	0.9	1.4	2.6	5.6
FCFS-Rer.	0.77	85.25	1531	-0.6	0.0	0.0	0.2	0.5	0.9	1.4	2.4	6.4
Big Delay - Rer	0.79	60.20	692	-0.3	0.0	0.0	0.1	0.4	0.8	1.2	1.9	3.7
FCFS-Ret	0.69	107.70	1244	-0.7	0.0	0.2	0.6	1.0	1.4	2.1	3.1	7.0
Big Delay - Ret	0.69	70.24	830	-0.9	0.0	0.1	0.4	0.8	1.1	1.7	2.4	4.0
FCFS - Rer - Ret	0.68	102.49	1150	-0.9	0.0	0.2	0.6	1.0	1.4	2.1	3.0	6.5
Big Delay - Rer - Ret	0.70	69.09	829	-0.9	0.0	0.1	0.4	0.8	1.1	1.6	2.4	3.9
Big Delay - Ret - XPT-4min	0.85	62.16	692	-0.3	0.0	0.0	0.2	0.5	0.9	1.3	2.0	3.7
Big Delay - Ret - XPT-5min	0.88	67.78	742	-0.3	0.0	0.0	0.2	0.5	0.9	1.4	2.1	3.9
Big Delay - Ret - XPT-6min	0.94	77.85	802	-0.3	0.0	0.0	0.3	0.6	1.1	1.6	2.6	4.7

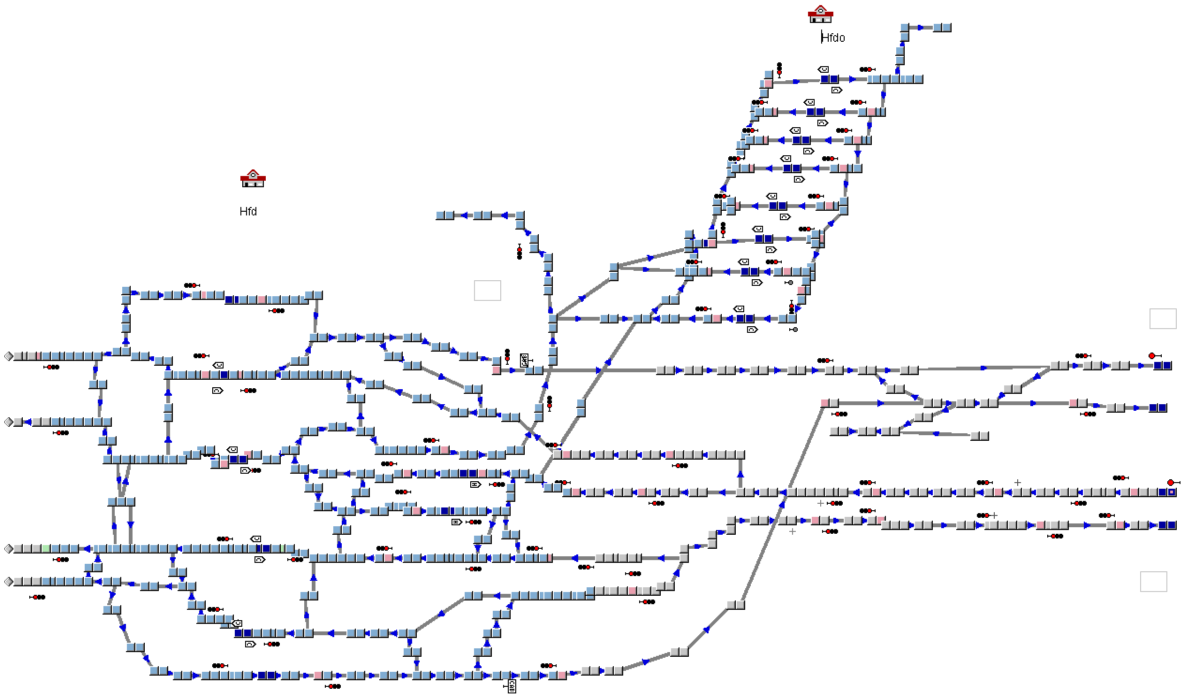
Appendix F

Impressions of the model and the data analysis

F.1 OpenTrack






Hfdo
Hfd

F.2 Matlab


```
close all
clear all
clc

sessie='18_2_2d';

XPT=[];
list=[];
calc=[];
[y,z,dat]=xlsread([sessie '.xlsx']);
[cor,y2,z2]=xlsread('corrector.xls');

for i=18:size(dat,1)
    if (strcmp(dat(i,4),'Hfd') && ~strcmp(dat(i,7),'HH:MM:SS') && ~strcmp(dat(i,15),'XX:XX:XX'))
        rawdelay=str2num(dat{i,16});
        [row,col]=find(cor(:,1)==dat{i,3});
        realdelay=rawdelay-cor(row,2);
        list=[list; realdelay];
    end
end
list=sort(list);
min=list(1,1)/60;
tsize=size(list,1);
for i=1:9
    if mod(((i/10)*tsize),1)~=0
            distr(i)=(list(floor((i/10)*tsize),1)+list(floor((i/10)*tsize)+1,1))/120;
    else
            distr(i)=(list((i/10)*tsize,1))/60;
    end
end

%XPT calculation
for r=1:30
    for c=1:7
        for i=18:size(dat,1)
            if (dat{i,1}==r && strcmp(dat(i,4),'Shl'))
                t=str2num(dat{i,12});
                if (dat{i,3}==(200+2*(c-1)))
                    XPT((r-1)*7*2+c,1)=t;
                elseif (dat{i,3}==(300+2*(c-1)))
                    XPT((r-1)*7*2+c+7,1)=t;
                elseif (dat{i,3}==(1200+2*(c-1)))
                    XPT((r-1)*7*2+c,2)=t;
                elseif (dat{i,3}==(1300+2*(c-1)))
                    XPT((r-1)*7*2+c+7,2)=t;
                end
            end
        end
    end
end

XPT2=[];
for i=1:size(XPT,1)
    if XPT(i,1)~=0
        a=XPT(i,1);
        b=XPT(i,2);
        c=abs(a-b);
        if c<=30
            XPT2=[XPT2; a b c 1];
        else
            XPT2=[XPT2; a b c 0];
        end
    end
end
XPT3=XPT2(:,4)';
xptper=sum(XPT3)/length(XPT3);
mean=mean(list);
max=max(list);
labels = {'XPT gehaald','gemiddelde delay','maximum delay','10%','20%','30%','40%','50%','60%','70%','80%','90%','min'};
total=[xptper mean max distr min];
xlswrite([sessie '_results.xlsx'],labels,'results','A1');
xlswrite([sessie '_results.xlsx'],total,'results','A2');
```