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Estimating the capacity of a stabling yard with the implementation of 100% servicing

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Preface

This thesis marks the completion of the Master Civil Engineering, track Transport & Planning at Delft University of Technology. I worked on this thesis in cooperation with the department Behandelen & Opstellen from ProRail and NS. I was an intern at ProRail during the study. I started work on the study in July 2017 and will defend my thesis on the 6th of July 2018.

During this study I learned a lot, both in regard to the subject matter and the organization that ProRail is. In the end I spend a few more months on the study than originally planned, but I am pleased with the result that now lies before you. Rushing to finish on time would have had a negative effect on the quality of this study.

I would like to thank the people directly involved in this thesis. My graduation committee consists of Serge Hoogendoorn, Rob Goverde and Jan Anne Annema from Delft University of Technology, as well as Johan Schouten from ProRail. Even though I did not ask for it as often as maybe I should have, they were always willing to answer questions and review sections of this thesis. I would also like to thank Hugo Thomassen, who started out as my supervisor at ProRail, but was forced to hand over this responsibility when his time at ProRail came to an end. Hugo offered me the internship at ProRail and made sure I had the contacts I needed to start my research. I would also like to thank the people at ProRail and NS that invested time in supplying me with the data needed.

Michiel van Marsbergen,
Delft, 29 June 2018

Executive summary

In this study a model is created that estimates the capacity of a stabling yard with the implementation of the 100% servicing concept. The 100% servicing concept is developed by Dutch rail operator NS with the goal to improve the quality and reliability of train services by increasing the frequency at which servicing tasks are performed. The service needs for all trains become similar and tasks are performed in a fixed order at centralized locations on the stabling yard, which makes planning at shunting yards a lot easier and the service process more efficient. Within NS and ProRail, some people think that 100% servicing could lead to an increase of the total stabling capacity at some stabling yards. With the rapid expansion of the fleet of NS stabling yards are reaching their capacity, so additional capacity is needed. The scale of the potential benefits of 100% servicing are however unknown and depend on the location characteristics. Several tools and models exist that calculate capacity of track sections or rail yards, but they are often complicated and do not take the specific characteristics of 100% servicing into account. This study aims to provide ProRail and NS with a tool that can quickly provide an insight in the potential effect of the introduction of 100% servicing at a certain location. It also aims to allow a quick estimate of the influence of adaptations to the infrastructure layout or the service process on the total stabling capacity. The following research question has been formulated in order to reach the goal of the study:

How can the stabling capacity of a stabling yard be estimated with the implementation of 100% servicing?

The research question is answered by developing an analytical model that uses specific characteristics of the infrastructure layout and service schedule of a stabling yard to estimate the stabling capacity. It also uses some average values and assumptions for this calculation, mainly in relation to the shunting of trains.

Service process characteristics

In order to answer the research question the current stabling process is assessed. Stabling of trains consists of the parking, cleaning and performing small maintenance tasks of trains at moments they are not needed in active service. The layout of a stabling yard has an influence on the stabling capacity. Stabling yards can have a carousel or shuffleboard layout, or a hybrid form. Two servicing types exist: low servicing and carousel servicing. With low servicing trains are serviced at the track they are parked at, while with carousel servicing trains are fully serviced on one track and parked on another. Only exterior cleaning is performed separately. Five main tasks are performed at stabling yards: exterior cleaning, interior cleaning, technical checks, repairs, and shunting and composing of trains. Each task has to be performed with a certain frequency. This frequency can differ between train types. The time tasks take can also differ between train types.

Stabling yards have a certain stabling capacity. This is defined as the amount of trains that can be parked and serviced on the yard at the same time, usually between the evening rush and morning rush. As train lengths are usually not constant, stabling capacity can be presented in standard or average amount of carriages or meters. The capacity of a stabling yard has several components: the physical stabling (i.e. parking) capacity, servicing capacity and shunting capacity. The actual capacity of a stabling yard is the lowest of these components. In the current service process, variability in the arrival times of trains, mainly caused by disruptions on the network, makes planning on stabling yards difficult and often shunting movements have to planned ad hoc. This leads to inefficiencies in the overall service process, which negatively affects the stabling capacity.

The 100% servicing concept is an evolution of the Pitstop strategy and the 4J-approach of NS. It also uses elements of the Lean Six Sigma methodology to remove waste from the process. The concept was first developed in Zwolle, where the side-by-side operation of two adjacent service locations causes significant inefficiencies. The servicing process with 100% servicing is divided into seven steps: leaving active service, buffering and composing of trains, exterior washing, main servicing, additional servicing (optional), parking and entering active service. Buffering is needed to feed trains through the process at a steady rate. The main difference with the current service process is the increase of frequency of the performance of tasks that directly influence passenger comfort. Another important difference is the structure of the process as an upgraded carousel process with a standardized duration of process steps: the takt time. A standard duration of the main service step is determined and all shunting movements are planned to assure trains are at this step at the correct time. A buffer is added to assure trains start the service process at the right time to align with the takt time.

The layout characteristics of a stabling yard can have an influence on the 100% servicing process. Yards with one central switch complex and yards with main tracks running through them are likely to be less efficient. Yards that can feature all steps behind one another, eliminating crossing movements of trains, can realize the most efficient process. Six capacity elements influence the total stabling capacity: physical stabling capacity (parking), main service capacity, additional service capacity, exterior washing capacity, buffer capacity and shunting capacity. The 100% servicing concept can have a positive influence on the capacity of a stabling yard though the separation of stabling and servicing. The simplification of planning can also lead to more capacity. The increase in tasks performed and the potential need for more shunting movements could also cause a reduction of stabling capacity.

Model for capacity estimation

In this study an analytical model is created using the programming language Python as a tool to estimate the stabling capacity with the implementation of 100% servicing. It is created for use on the Dutch rail network, but could be used for other locations after some adaptations. The model takes data on the track layout, switch occupation of other train traffic (not using the stabling yard) and arrival- and departure characteristics of trains using the location as input, as well as several parameters related to the characteristics of the service process. It produces an estimate of all sub-elements of the total stabling capacity in order to show which element is the bottleneck. The final stabling capacity is defined as the lowest capacity of the sub-elements. Variability is not taken into account, so it is possible that these capacities can only be achieved in an ideal situation. An example of this is the even distribution of the arrival pattern of trains, which especially influences the buffer capacity. The capacities are presented in meters of train and amount of standard carriages per night shift.

The model uses several assumptions and standard values used by ProRail and/or NS to estimate the capacities. An important assumption is that NS has to provide enough personnel in order to reach an average percentage of 92% of trains that are fully serviced within the takt time. The personnel aspect is excluded from this study. For the shunting capacity the model uses the shortest route for all shunting movements. The track length data obtained from ProRail is incomplete, so the length of a route is estimated using some average values. The model assumes all shunting movements will use the shortest route possible. The model does not produce an optimal shunting plan where the movements of other trains are taken into account. The model also assumes all combinations of tracks assigned to consecutive steps (for example exterior washing and main service) have equal demand. No route optimization occurs. This could lead to some illogical route usage, which could negatively affect the shunting capacity. Furthermore, for the exterior washing and shunting capacity the model uses average values for train length and duration of direction changes. The buffer capacity is not calculated directly, as many components are unknown. Instead, buffer capacity is calculated for several assumed values for the time trains on average spend in the buffer.

The validity of the model has been assessed using the base scenario of the case study of Eindhoven. The results from the model have been verified using the available data from NS and ProRail. The physical stabling capacity, exterior washing capacity and main service capacity correspond well with the expected values derived from the data. However, for the shunting capacity this method was not available. The results have been checked to determine if they are comparable to the expectations. It turned out that the validity of the shunting capacity is limited due to the assumptions made in order to calculate it. In reality an optimized shunting plan would be created, which would use the available infrastructure as logically and efficiently as possible. Quantification of the validity of the shunting capacity requires a comparison with a verified model or a manual simulation, which has not been performed in this study. Deeper analysis by the user of the model of the use of infrastructure elements as determined by the model could lead to an adjusted value in some cases. Due to the limited validity of the shunting capacity the model can only be used to provide rough estimates of the capacity of a stabling yard with the implementation of 100% servicing. It is more accurate when using it to determine the effect of adaptations, as the same assumptions are used in both cases.

Case studies

Two case studies are performed in order to show the working of the model. The Dutch locations of Eindhoven and Zwolle are assessed. These are two locations with a very different layout. In Eindhoven all tracks are parallel, while in Zwolle tracks are more located in sequence. In the case study of Eindhoven four scenarios are assessed. From these scenarios it becomes clear that Eindhoven as a stabling location is not well suited for the implementation of 100% servicing. The infrastructure cannot handle the amount of additional shunting movements that a change to 100% servicing causes. Almost all shunting movements require a change of direction, causing this element to be the bottleneck. The options to increase the shunting capacity are limited and can only marginally increase shunting capacity. Overall the implementation of 100% servicing in Eindhoven is more likely to decrease capacity than it is to increase it, unless extensive adaptations to the infrastructure are made.

From the case study for Zwolle it becomes clear that the track layout of this location is much more suitable for the implementation of 100% servicing. This has to do with the fact that in Zwolle the consecutive steps of the process are located in a good order, which significantly reduces the need for a change of direction. Instead of the shunting capacity, the buffer capacity turned out to be the main bottleneck in Zwolle. Several adaptations were made to improve this element. These adaptations did cause a decrease in shunting capacity, but overall 100% servicing could increase the total stabling capacity in Zwolle compared to the current situation. This corresponds with the expectations of the effect of 100% servicing on the stabling capacity in Zwolle.

Conclusions and recommendations

The main conclusion from this study is that a simple tool to estimate the stabling capacity with the implementation of 100% servicing can be used as a first assessment for the suitability of specific stabling yards for the implementation of 100% servicing, as well as for analysis of the general impact of infrastructure of process alterations. It cannot be used for exact calculation of the stabling capacity, as the assumptions negatively influence the validity of the model. Especially the validity of the shunting capacity is limited due to the extensive assumptions made related to the routes trains will use when shunting. These assumptions were however necessary in order to keep the model simple and easy to use. The limited validity of the results of the model limits the uses of the model to first assessments of locations. No important decisions should be made using only the results of this model.

The case studies showed that the layout of a stabling yard has a significant influence on the capacity with 100% servicing. It showed that especially the need for changing directions during shunting movements can have a large effect on the capacity. The case study also showed that the buffer capacity can play an important role. This does however strongly depend on the arrival process of trains.

The recommended use of the model is only for the first assessment of the capacity of a stabling yard with the implementation of 100% servicing. It can be used to decide if a location is worth a more elaborate study into the effects. This could be done using a more extensive and accurate model, especially one that creates an optimized shunting plan. It could also be done using step by step manual simulation of shunting movements on the stabling yard. The main areas where more research could be done are the shunting and buffer capacity. A more detailed analysis of the accuracy of the estimated shunting capacity would provide a better understanding of the validity of the model. A study could be done were a full-scale model that creates an optimized shunting plan is compared to the model created in this study. The buffer capacity is an important part of 100% servicing, as the actual arrival pattern of trains is usually not evenly distributed. If insufficient buffer capacity is available, trains might have to be held at platform tracks, potentially interrupting train operations. A good understanding of the expected demand for buffer capacity is therefore an important area for further research.

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1. Introduction

This introduction provides an insight into the term stabling. Stabling and the stabling process are central in this study. A short introduction to the term stabling is provided in chapter 1.1. As this study mainly focusses on the Netherlands, chapter 1.2 provides an insight in the Dutch rail network and locations of stabling yards. In chapter 1.3 the problem and purpose of the study are described. Chapter 1.4 presents the research questions. In Chapter 1.5 the research methodology is described and chapter 1.6 provides an overview of the report structure.

1.1 Stabling

Demand for train transport is not consistent over the day. The morning- and evening rush hour are the busiest periods. Train operators need a large enough fleet to satisfy demand in these periods. Outside of rush hour, fewer trains are needed. Especially at night most of the fleet is not needed. In these periods trains are stabled. In essence stabling is the parking of trains that are not needed. However, trains also have to be cleaned, mechanical checks have to be performed and unscheduled maintenance has to take place. This is the service process, as described in (Janssens, 2017). This can only be done in the period trains are not in active service, which is the case when they are stabled. Stabling usually takes place at stabling yards. Stabling yards are locations where several stabling tracks are located together, usually besides the main railway line. Temporary stabling at platform tracks is also possible, but trains cannot be fully serviced here. Stabling yards are often located on strategic points in the rail network, usually near the larger stations. The service tasks that can be performed at specific stabling yards depend on the equipment present.

1.2 The Dutch rail network

The Dutch rail network consists of over 7.000 kilometers of track. In 2015 over 3,3 million train services were facilitated on this network. On average passengers made 1,1 million trips daily in that year (ProRail, 2017). ProRail is the rail infrastructure manager in the Netherlands. Its main responsibility is the construction and maintenance of all rail infrastructure, as well as dividing the available infrastructure among operators and providing traffic control.

Several train operators provide train services in the Netherlands. Nederlandse Spoorwegen (NS) is the main rail passenger operator. NS currently operates a fleet of over 700 train units, consisting in total of over 3.000 carriages (ProRail; NS, 2017). All of these trains have to be serviced. The interior and exterior have to be cleaned and regular checks and repairs are necessary to ensure safe and comfortable operations. The servicing company for trains of NS is NedTrain.

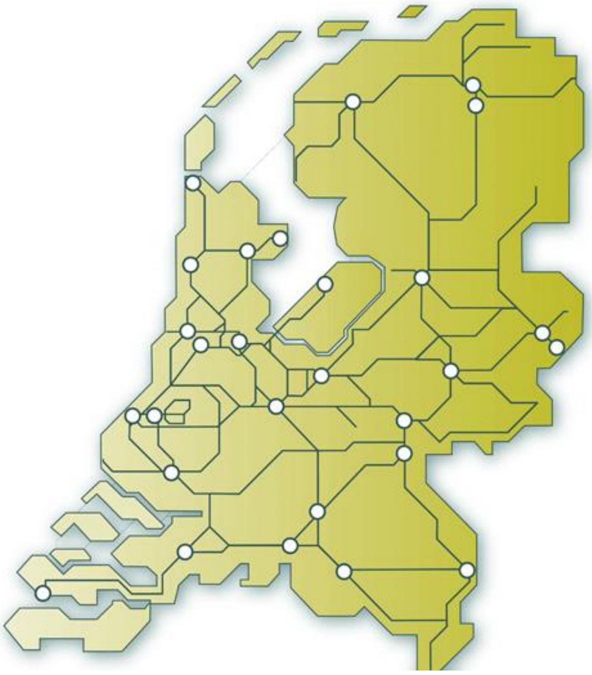

Figure 1: Overview of Dutch rail network and service locations (NedTrain, 2017)

NedTrain is a subsidiary of NS, but it also services trains of other operators. In the Dutch rail network a total of 33 NedTrain service locations or stabling yards are located on strategic points (NedTrain, 2017). Trains do not have one of these locations as base, but they operate throughout the network.

Figure 1 provides an overview of the Dutch passenger rail network and the NedTrain service locations. Some dots represent more than one location. The high-speed line and dedicated freight lines such as the Betuweroute are not included in this overview.

1.3 Problem statement and purpose of the study

1.3.1 Problem statement

In the coming years Dutch Railways (NS) and ProRail are expected to make big steps in the introduction of the Program 'Hoogfrequent Spoor' (PHS). This program contains the transition from a 4 Intercity trains per hour schedule on certain corridors to a 6 trains per hour schedule (ProRail, 2017). In order to accommodate this increase in frequency the NS has ordered new trains. During the day most trains will be used to execute the schedule, but at night they will have to be parked and serviced at stabling yards. The current capacity of the stabling yards dedicated to NS is insufficient to accommodate the extra trains needed for PHS. In addition, the current capacity to clean trains and perform technical checks will be insufficient when the new trains arrive. The shortage of capacity can be partly reduced with the completion of several projects that are currently being constructed or are planned for the near future. The budget for these projects is however insufficient to realize a large enough capacity increase. These projects will also not be completed fast enough, so additional measures are needed to ensure all trains can be parked and serviced.

With the current stabling yards reaching their capacity, Dutch Railways is experiencing problems with reaching the desired quality levels of the train services provided. The standards set by NS regarding internal and external cleanliness of the trains, as well as technical state of the fleet, are becoming increasingly difficult to meet. The cleanliness of the trains is part of the conditions included in the concession for the main network, on which NS is the only operator. Not meeting these conditions could lead to NS losing the concession in the future. In order to improve the cleanliness NS is developing the 100% servicing concept. In this concept the stabling process is significantly changed. In the current service process only the tasks that have reached their predetermined deadline are performed. For example, the exterior of a train has to be washed every seven days and most B-checks of trains should be performed every other day. The fact that not all stabling yards have the equipment needed to perform these tasks and the unexpected nature of the arrival process of the trains and the work that needs to be done on them makes meeting these deadlines more difficult. On busy nights there is insufficient time and resources to perform all required tasks and send the train out on time.

In the 100% servicing concept some of the tasks will be performed every time a train reaches a location where this concept is implemented. The main focus is on tasks that have an effect on the public appreciation of NS, such as interior and exterior cleaning. Some additional tasks that directly affect public appreciation will be performed as standard, such as checking the intercom and air-conditioning systems and state of the interior. 100% servicing will only be implemented on the largest stabling yards, because the smaller yards often don't have the equipment needed. Since most trains of NS travel across most of the network, the idea is that the trains will reach a 100% servicing location often enough to improve the overall quality.

Another part of 100% servicing is the removal of 'waste' in the process, which is necessary to accommodate the extra tasks. In the current servicing process the productivity of the staff at a stabling yard is low, mainly because of the fact that they often have to travel from one train to another and to the base location or the warehouse and back. In the 100% servicing concept the trains will 'flow' through the process, which means tasks are concentrated at certain locations on the stabling yard and trains move between them. This way personnel does not have to travel from one track to another (as often) anymore. In order to assure sufficient time to perform each task, a standard duration for each step is implemented. If a train needs more time for a certain task, it is taken to a separate track to not affect the 'flow' of the other trains. This, combined with the increased productivity of personnel, will likely have an effect on the capacity of a stabling yard. The amount of trains that can be serviced could increase. Combined with a potentially more efficient use of the physical infrastructure this could lead to a higher stabling capacity. As 100% servicing is a new and untested concept, the exact scale of the potential capacity increase is unclear. ProRail and NS would like to know what this potential is, as they are occupied with finding additional capacity wherever they can find it. Other rail operators might also be interested in the effects this concept has on the quality of train services and the stabling capacity.

1.3.2 Purpose of the study

The main objective of this study is to develop a model that can provide a clearer picture of the potential effects on the stabling capacity at specific locations they can expect from the transition to stabling according to the 100% servicing concept. It should be focused on the Dutch rail network, but also be usable for stabling yards in other countries. Some people within ProRail and NS expect a 'significant increase' in capacity, while others are skeptical about there being any increase. With the stabling capacity becoming as critical as expected in the coming years, a clear picture of the local shortages will help ProRail and NS prioritize the planned projects within the limited budget. Because the effect the 100% servicing concept might have on the stabling capacity is probably largely dependent on local characteristics of the stabling yard, this effect will have to be assessed for individual yards. This study therefore aims to provide ProRail and NS with insight in the locations where an increase in capacity can be expected. In order to do that a model will be created to estimate the capacity of a stabling yard using a set of characteristics. Other models exist that are capable of doing this, but this model aims to better incorporate the characteristics of 100% servicing and be simpler and therefore quicker than other models. The model also provides the option to make changes to the infrastructure and the service process, so it can be used to provide an estimate of the effect of certain changes. This study also aims to show ProRail and NS whether the model works by doing a case study of two locations that are interesting for 100% servicing, but contain some difficulties for the implementation of a smooth servicing process.

1.4 Research questions

1.4.1 Main research question

In order to reach the research objective, the following research question has been formulated:

How can the stabling capacity of a stabling yard be estimated with the implementation of 100% servicing?

1.4.2 Subquestions

In order to be able to answer the main research question, the following subquestions have been formulated:

1. What are the characteristics of the current stabling process?
2. What is the definition of stabling capacity?
3. What are the characteristics of 100% servicing and what are the differences compared to the current stabling process?
4. Which models and algorithms exist to estimate the capacity of a stabling yard?
5. What steps does the model need to contain to estimate the capacity of a stabling yard?
6. What are the limitations of the model?

1.5 Research methodology

In order to be able to set up a model to estimate the capacity of a stabling yard as described in the main research question, a thorough understanding of 100% servicing is needed. Furthermore, the current service process also has to be understood. A lot of aspects of the current service process are still relevant for 100% servicing and therefore have to be included in the study. It is also desirable to be able to understand the differences between the current service process and 100% servicing, so a description of this is provided. The research starts with a description of the current service process and the 100% servicing concept. This leads to a set of requirements for the model to meet. The main source of information for such a description is often literature. For a description of the current service process there was literature available, although visits to stabling yards and contact with employees have also contributed. Since 100% servicing is a new concept, very limited literature is available. The main source of information for the description of the concept is interviews with people who are involved in the development and testing of the concept.

Other models and algorithms have already been developed that are capable of creating a shunting plan and/or determining the capacity of a stabling yard. A literature study is done to provide basic knowledge for the model created in this study. Based on the literature, the model created in this study is an analytical model that uses mathematical formulas. It is programmed in Python. The exact shape of the model is somewhat determined by the limited programming experience of the researcher, but is mostly derived from methods in other models found. In some cases personal insights are used. Some support can be provided by the department of NS that is currently developing a model to estimate the capacity of a stabling yard. This model is however not directly suitable for the determination of the effect of 100% servicing, which is why it is used as inspiration. The model that is created has to be validated. This will partly be done by comparing the model results to the expected values from the available data. If no such data is available, the model results are assessed in more detail and statements are made regarding the likelihood of the results being accurate.

When the model is created the capacity of two stabling yards in the Netherlands with 100% servicing can be estimated. This is compared to the current capacity that is used by NS and ProRail. Special care has to be taken to make sure the base scenarios are as equal as possible. For these two locations a full study will be conducted using the model. The bottleneck in capacity will be estimated. Solutions will be provided for this bottleneck and the capacity will be re-estimated. A scenario with a different subdivision of tracks for certain tasks can also be assessed. Three scenarios are created for both locations and assessed, in order to try to increase the capacity from the base scenario. The combined results provide a picture of the suitability of the location for 100% servicing and possible adaptations that would increase capacity.

1.6 Report structure

The structure of this report consists of six chapters, an executive summary and several appendices. The first chapter is this introduction chapter. In Chapter 2 the current service process is described. It elaborates what a stabling yard is and which actors are involved, which tasks are performed at a stabling yard, which characteristics of trains influence the stabling process, how the servicing process is set up, how the planning for a stabling yard is made and which definitions of stabling capacity are used. The 100% servicing concept is described in Chapter 3. It treats the main goals of 100% servicing, the development of the concept, the other programs that inspired 100% servicing, the characteristics of the 100% servicing concept, the main differences with the current service process and the potential effect of the concept on the stabling capacity.

In Chapter 4 the creation of the model that can be used to estimate the influence of 100% servicing on the capacity of a stabling yard and the required data are described. The desired output, required input data and model steps are described, as well as the validity of the model. In Chapter 5 the model created in Chapter 4 is used to analyze the effect of 100% servicing on two existing service locations as a case study. The locations chosen are Eindhoven and Zwolle. In this chapter the choice for these locations are elaborated and the outcomes of the different steps of the model are presented. This chapter ends with a conclusion about the suitability of these locations for the implementation of 100% servicing. In Chapter 6 the conclusions of this study are presented. Additionally, recommendations are provided concerning the use of the model resulting from this study and the areas where further research might be necessary.

2 Current stabling process

In this chapter the current stabling process will be elaborated. Chapter 2.1 elaborates what a stabling yard is and where they are located, as well as which companies or organizations play a role in the stabling process. Chapter 2.2 provides an overview of the tasks that are performed at stabling yards and what they include. Chapter 2.3 gives an insight into the characteristics of the different types of rolling stock NS operates. This includes the differences in service requirements. Chapter 2.4 gives a detailed description of the current service process and elaborates the planning at stabling yards. In chapter 2.5 the different definitions of stabling capacity are elaborated. In chapter 2.6 a summary of this chapter is provided.

Most of the information presented in this chapter has been obtained from the thesis of S. Janssens (Janssens, 2017), an overview of data called SSOI collected by ProRail and NS (ProRail; NS, 2017), personal experiences from visits to NedTrain service locations in Zwolle and Amsterdam Watergraafsmeer and contact with personnel at these locations.

2.1 Stabling yards

Throughout the Dutch rail network a total of 33 stabling yards are located at strategic places. Stabling yards are locations were passenger trains are parked when passenger demand is low and were they are being serviced. The servicing aspect is the main difference between a stabling yard and a rail or shunting yard, which are mainly used for parking and shunting freight trains.

2.1.1 Companies involved in the stabling process

Before 1995 Nederlandse Spoorwegen (NS) was responsible for everything that is related to railway operations in the Netherlands. It was the only operator for passenger and freight transportation, as well as the owner of the rail infrastructure. After 1995 the desire of the European Union to liberalize the railways came into effect in the Netherlands. In the next decade NS was slowly transformed to just a passenger train operator (NS, 2017). In 1999 the separation of the maintenance department was completed with the change of the name to NedTrain. NedTrain is still a subsidiary of NS. In 2000 the freight branch of NS merged with DB Cargo to form Raillion (currently known as DB Cargo again). NS has no involvement in DB Cargo. In 2002 the infrastructure was officially handed over to the government, which in turn handed it over to ProRail in 2005, completing the separation of infrastructure ownership and rail transport. NS is now only responsible for passenger services on the main rail network in the Netherlands. Secondary lines are being transferred to other operators.

NedTrain is the main company that supplies service and maintenance for trains in the Netherlands. As a subsidiary of NS, it handles all maintenance, cleaning and the technical checks of the trains of NS, but it also offers its service to other operators. Other passenger operators in the Netherlands are Arriva, Syntus, Connexxion and Breng. These operators only operate on secondary lines and are not large enough to be able to financially operate all required maintenance facilities. They are however responsible for internal cleaning and technical checks of their trains. NedTrain provides mechanics to check the trains of NS and perform repairs, but it outsources the internal cleaning to a third party.

In the Netherlands virtually all rail infrastructure is managed by ProRail. ProRail is responsible for the construction and maintenance of the rail infrastructure, as well as assigning rail capacity to different operators and providing traffic control. Most of the tracks at stabling yards are owned by ProRail. Only the tracks in and around maintenance centers are owned by NedTrain. All licensed operators can request usage of tracks at stabling yards owned by ProRail. At some stabling yards this leads to a division of capacity between two or more operators. Tracks that are requested by two or more operators will be divided by ProRail in consultation with the operators. ProRail has the responsibility to provide enough stabling capacity to satisfy the needs of all train operators in the Netherlands. Coordination with the operators to determine future capacity demand is therefore key.

2.1.2 Characteristics of stabling yards

Each stabling yard in the Netherlands has its own characteristics. Stabling yards can vary significantly in size. This has an effect on the available facilities at the location. Facilities for tasks that do not have to be performed daily are often only located at the larger locations. The larger locations are mostly located near the largest stations. Examples of large stabling yards are Amsterdam Watergraafsmeer, Den Haag Binckhorst, Rotterdam and Eindhoven. These locations can handle at least 150 carriages per night. Smaller locations are often located at the edges of the network. Examples are Den Helder, Vlissingen and Enkhuizen. These locations can handle fewer than 50 carriages per night.

Stabling yards can also differ in layout type. In general two infrastructure layout types exist: a shuffleboard layout and a carousel layout. A stabling yard with a shuffleboard layout is characterized by a lot of dead end tracks. The yard can often only be accessed from one side through a central switch complex. At these stabling yards trains have to be parked according to the Last In First Out (LIFO) principle. Trains that arrive last will have to leave first, because otherwise trains can become blocked in. An example of a stabling yard with a shuffleboard layout is Amersfoort Bokkeduinen. This yard can only be accessed from the east and only has dead end tracks. Note that several dead-end tracks on the east side of the yard can only be accessed after changing direction at a track on the west side. Figure 2 shows the general layout of Amersfoort Bokkeduinen.

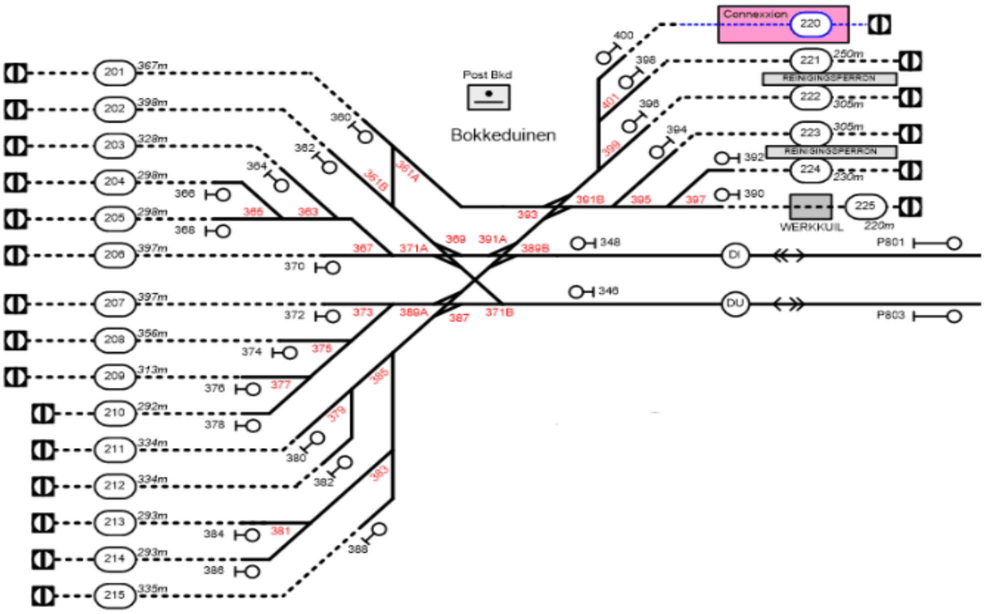

Figure 2: Schematic overview of Amersfoort Bokkeduinen (Zeegers, 2017)

A stabling yard with a carousel layout has a central switch complex on both ends, so trains can enter and leave a track on either side. In some cases trains can enter and leave the yard on both sides, but a stabling yard with a carousel layout can also have only one access track. In that case on the other side of the yard there are one or more tail tracks where trains can change direction. Trains do not have to be parked according to the LIFO principle, but the direction in which the train has to leave the yard does have to be taken into account. An example of a stabling yard with a carousel layout is Amsterdam Watergraafsmeer. It can be accessed from the eastern and western side. It has tracks with servicing platforms on the western side and tracks without any facilities except a path for the train driver on the eastern side, separated by a central switch complex. Figure 3 shows the general layout of Amsterdam Watergraafsmeer.

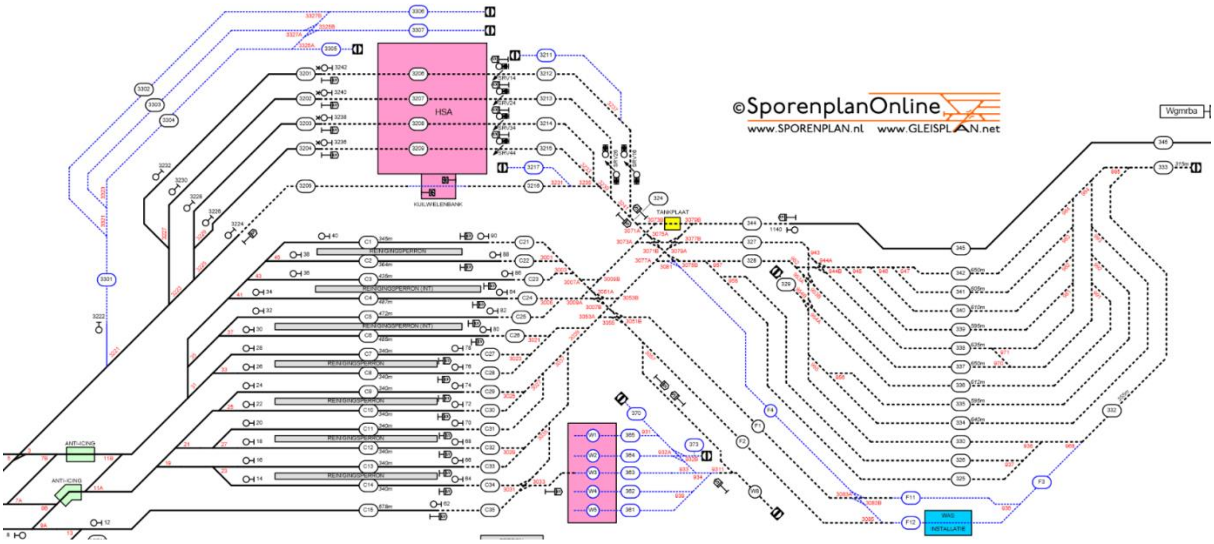

Figure 3: Schematic overview of Amsterdam Watergraafsmeer (Zeegers, 2017)

Stabling yards can also differ in the available facilities. These facilities determine which tasks can be conducted at the location. The yard in Leidschendam has the main maintenance center of NedTrain. Large repairs are conducted here. Five stabling yards are equipped with a Technical Center. Smaller repairs that cannot be conducted outside can be performed here. Maintenance pits and aerial platforms are also present at selected locations. These are needed for some repairs. Washing machines are only present at twelve of the 33 service locations. Other equipment needed to clean trains or perform technical checks is present at all locations. Appendix 1 provides an overview of all NedTrain stabling yards and the general facilities that are present at these locations.

2.1.3 Servicing types

Besides a layout type stabling yards can also be characterized on servicing type. Two main types exist: low servicing (in Dutch: laag servicen) and carousel (not to be confused with the carousel layout type). Low servicing is a servicing type were a servicing path on ground level (hence the low) is available besides every stabling track. This way trains are serviced on the track they are parked on, limiting movement of trains. Personnel has to walk from train to train. It is mainly but not exclusively used on yards with a shuffleboard layout. An example of a carousel type stabling yard where low servicing is used is Hoofddorp.

Carousel servicing often has several tracks with a servicing platform at door level and tracks without facilities. After being serviced alongside a platform a train will be moved to a stabling track, and the next train will move to the servicing track. This leads to more train movements compared to low servicing, but fewer facilities are needed and personnel does not have to walk as much. Carousel servicing is mainly but not exclusively used on stabling yards with a carousel layout type. An example of a shuffleboard type stabling yard where carousel type servicing is used is Amersfoort Bokkeduinen.

2.2 Characteristics of tasks

The tasks that are performed at NedTrain service locations can be divided into five different categories. These categories are: exterior cleaning, interior cleaning, checks, repairs and formation of trains. Not all service locations are equipped to be able to perform all tasks. An example of this is exterior cleaning, as only twelve service locations are equipped with a washing machine. This chapter will describe the five categories of tasks.

2.2.1 Exterior cleaning

The exterior cleaning of trains is performed at a Train Washing Machine or TWI. Twelve of the 33 service locations of NedTrain are equipped with a TWI. Exterior washing of trains does not happen on a daily basis. Trains are scheduled to be washed with soap and water every seven days. Trains can also be washed with oxalic acid, which is stronger and removes certain types of dirt that can't be removed with soap. This is scheduled to happen every 63 days. The exterior washing of trains is not considered a critical task, which means trains are not excluded from service if the deadline has passed. It is usually not planned beforehand and only executed if necessary. Because of this and the fact that not all locations are equipped with a TWI, trains are regularly not washed as often as is desired.

There are several different types of washing machines. Most machines require the train to drive through the TWI at a low and constant speed. Some (mostly older) washing machines are located at tracks that are not electrified, which means they have to be driven through the washing machine by a diesel-electric shunting locomotive. The speed at which the train has to drive through the machine can be different. Some TWI's are designed for higher speeds, such as the TWI in Enschede. In Rotterdam the train is parked in the TWI and the washing equipment moves along the train. The work load of the TWI's can also differ significantly. The TWI in Den Haag Binckhorst is for example much busier than the TWI in Vlissingen.

Another type of exterior washing is graffiti removal. Vandalism with graffiti on trains is a large problem in the Netherlands, as it happens frequently. Graffiti should be removed as quickly as possible, as it negatively affects the appearance of the trains and therefore the experience of passengers. Graffiti removal can only be done at certain locations that are equipped with the specialized equipment needed. Graffiti removal is not planned due to its unexpected nature.

2.2.2 Interior cleaning

The interior cleaning of trains is performed every day at all of the service locations of NedTrain. All elements of the interior are cleaned if necessary. The seats, tables, floors and toilets are the main focus of the interior cleaning process, as well as the emptying of the garbage bins. The windows and walls are also cleaned if necessary. The interior cleaning is outsourced to a third party. Trains can be excluded from service if not cleaned properly, but this is not standard practice. Interior cleaning is generally planned in advance, which is possible because all trains require roughly the same service.

Graffiti removal is occasionally also needed on the interior of trains. The process is often different from graffiti removal on the exterior, as repainting or replacing a component might be the only option to restore the vandalized component. It has to be done by trained personnel at locations that have the required equipment. Interior graffiti removal is not planned.

2.2.3 Checks

Technical checks of the trains are an important part of the servicing process. Several different types of checks exist. An A- and B-check exist for most types of trains. The B-checks consist of a visual inspection of the major technical components of the train, such as the braking system, status of the wheels and the pantograph. The functionality of critical safety systems is also checked. For most types of trains this check has to happen every other day, but there are some types that are checked daily. For most trains A-checks are performed every 12 days, but some (mostly older) train types have to be checked more often. These checks are more extensive, as the functionality of the main components is checked. The state of the interior is also checked during an A-check.

Trains that run on the High-Speed Line (HSL) or operate internationally have different requirements for technical checks. These trains have to be checked every 24 hours to ensure safe operations with high speeds. The 24-hour checks are similar to the abovementioned A-checks. All checks have to be performed on time, as by law trains cannot be released for active service otherwise.

2.2.4 Repairs

Repairs can be the result of faults found during the technical checks, reported during the service of the train or because components have reached their technical limit. Only the last category can be planned well in advance of the repair taking place. It depends on the location which repairs can be executed. Some service locations are equipped with a Technical Centre (TC), where extensive maintenance can be conducted. Pits and platforms to be able to work underneath or on the roof of trains are available on more locations. Specialized repairs have to be done at NedTrain’s main maintenance center in Leidschendam or the refurbishment and overhaul center in Haarlem. Repairs can either be necessary or desired. Necessary repairs are mainly safety related, but can also be comfort related. Desired repairs are mainly repairs that affect passenger comfort, such as ripped seat covers and broken air-conditioning units. If the need for a necessary repair is found at a location that is not equipped for this repair, the train has to be brought to a different location. If a desired repair cannot be conducted, the train will continue with the fault in revenue service until a location with the right equipment and enough spare resources to perform the repair is reached.

2.2.5 Formation of trains and shunting

An important task within the servicing process is the formation of trains. The main goal is to make sure trains leave the stabling yard in the morning in the right composition. This means that the trains are the correct type and have the correct length. On average about 80% of the trains arrive in the same composition in the evening as they have to leave in in the morning. The remaining 20% of the trains has to be separated after arrival and/or combined before departure. At most stabling yards more than one train can be parked at a stabling track, so the trains have to be parked in the correct order for their scheduled departure in the morning. This process is planned as much as possible, but last minute changes to the arrival of trains can cause adaptations to the planning. These changes are mainly caused by disruptions in the timetable.

Trains might also have to be moved between their arrival and departure, for example to visit the washing machine (TWI) or in order to be parked on the correct track. Depending on the amount of movements and the layout of a stabling yard, planning these movements can be quite a challenge. Not all movements such as a visit to the washing machine are planned beforehand, because it is often not fully known which tasks will be performed during a shift. If a lot of shunting movements have to be performed this can influence the servicing capacity of a stabling yard.

2.3 Characteristics of rolling stock

All NedTrain service locations are equipped to service more than one type of train. This is necessary because the type of train that is used on certain routes can change every year. Each type of train has its own requirements with regards to service needs. Furthermore, the rolling stock type influences the duration of most of the tasks mentioned in the previous chapter. NS has 9 different types of trains for national services and a further 5 types of trains for international services. Most trains are of the Electric Multiple Unit (EMU) type, which means they are train units that have a driver's cabin on both sides, can often be coupled to other train units and have a permanent configuration. Most EMU's appear in two different configurations, which mainly differ in length. NS has about 700 train units consisting of just over 3000 carriages operating nationally. NS is also responsible for the maintenance of a further 20 international train units consisting of 170 carriages. NS owns some of these international trains and operates them in cooperation with foreign operators.

NS train services can be summarized into three categories: sprinter, intercity and international. The different types of trains are usually categorized as one of these three categories. In this chapter the characteristics of all train types of NS are provided per category of train type. However, intercity trains can be used on sprinter train services and vice versa, but this is undesirable as it could have an effect on the punctuality and seating comfort. At some NedTrain locations trains of other operators than NS are also serviced. This study focusses on the service processes of NS, so the other operators are not included. Therefore the characteristics of the rolling stock of these operators are not included in this chapter. This includes the trains of Abellio, which is a daughter company of NS.

In this chapter the general characteristics of the trains of NS are provided. This includes the amount of units in the fleet, length over buffers, amount of carriages and locomotives (if applicable) per unit and average length per carriage. The amount of units in the fleet shows the current fleet composition. Units that have been phased out and/or demolished are not included. Locomotives are mentioned separately because they have different servicing needs compared to carriages, but do occupy stabling capacity. Locomotives are included in the average length per carriage.

2.3.1 Sprinter trains

Sprinter trains are mainly local trains. They usually stop at all stations along the line. These trains have a high acceleration and a relatively low top speed. NS has five different types of Sprinter trains in its fleet: the SGM, SLT, Flirt, DDAR and DM'90. The SLT and Flirt trains are relatively new, whereas the SGM and DDAR trains are old and scheduled to be retired in the near future. To replace them NS has ordered SNG trains, which are expected to be delivered in the coming years. The DDAR trains are the only double-decker trains that are classified as sprinter trains. They use a class 1700 electric locomotive in a push-pull configuration. The SLT and Flirt trains are designed as train sets with articulated carriages that are equipped with Jacobs bogies. This allows a design where passengers can move freely throughout the entire train unit, but it makes separating carriages at a service location very difficult. The DM'90 trains are the only diesel trains in the fleet of NS. Because they are scheduled to all be phased out by December 2017 they are not included in this study.

Table 1 provides an overview of the characteristics of the sprinter trains in the fleet of NS.

Table 1: Characteristics of Sprinter trains

	AMOUNT IN FLEET	LENGTH OVER BUFFERS (M)	CARRIAGES (+ LOCOMOTIVES)	AVERAGE LENGTH CARRIAGE
SGM-2	30	52.2	2	26.1
SGM-3	60	78.7	3	26.2
SLT-4	69	69.4	4	17.3
SLT-6	62	100.5	6	16.8
FLIRT-3	33	63.2	3	21.1
FLIRT-4	25	80.7	4	20.2
DDAR	18	97.3	3 (+1)	24.3

2.3.2 Intercity trains

Intercity trains are national trains that only stop on the larger stations, decreasing the travel time between cities. They usually have a lower acceleration compared to sprinters, but have a higher top speed. NS has the VIRM, DDZ, DDM and ICM in its main intercity fleet, as well as trains consisting of ICR carriages and two locomotives. The VIRM, DDZ and DDM are all double-decker trains, whereas the ICM trains and ICR carriages are not. The DDM trains use a 1700 series locomotive in a push-pull configuration. It is similar to the DDAR, with the main difference that it is longer.

On the corridor The Hague – Eindhoven NS uses trains consisting of 9 ICR carriages and 2 Traxx locomotives (one on either end). In the remainder of this report it will be named ICR-9. A special service is the Intercity Direct, which operates on the Amsterdam – Breda corridor via the high-speed line (HSL). It uses trains consisting of 6 ICR carriages and 2 Traxx locomotives (one on either end). In the remainder of this report it will be named ICR-6.

Table 2 provides an overview of the characteristics of the intercity trains in the fleet of NS.

Table 2: Characteristics of Intercity trains

	AMOUNT IN FLEET	LENGTH	CARRIAGES (+ LOCOMOTIVES)	AVERAGE LENGTH CARRIAGE
VIRM-4	98	108.6	4	27.2
VIRM-6	78	162.1	6	27.0
DDZ-4	30	101.1	4	25.3
DDZ-6	20	154.0	6	25.7
ICM-3	87	80.6	3	26.9
ICM-4	50	107.1	4	26.8
DDM	11	123.7	4 (+1)	24.7
ICR-6	17	196.2	6 (+2)	24.5
ICR-9	12	275.4	9 (+2)	25.0

2.3.3 International trains

NS International mainly operates train services to Belgium, France and Germany, some of which use the high-speed line (HSL). All international services are operated in collaboration with foreign railway companies, such as Deutsche Bahn, SNCF and NMBS. Thalys services towards Paris and Lille use high speed Thalys PBA and PBKA trains, which are based on the French TGV trains. Towards Germany NS uses both high speed ICE trains and lower speed trains consisting of German intercity carriages and a 1700 series locomotive. Towards Belgium NS operates trains consisting of ICR carriages and a Traxx locomotive. In December 2017 Eurostar services from London to Amsterdam will start. NS international will be a partner for this service. NS does not own any of the Eurostar trains, but it will provide some level of service. Therefore this train is included in this chapter.

Amsterdam Watergraafsmeer is the only service location in the Netherlands were the trains of NS International are fully being serviced. A specialized maintenance facility has been built for these trains. The trains of Deutsche Bahn are only cleaned in the Netherlands. This happens on a few dedicated servicing tracks on the west side of Amsterdam Central station.

NS operates all international services in collaboration with foreign railway operators. As a result, NS does not own all trains and carriages it uses for the execution of the schedule. For example, NS owns 2 Thalys trains and 3 ICE trains. More Thalys trains are owned by SNCF and NMBS, while more ICE trains are owned by DB. The trains owned by different operators often operate interchangeably on the international corridors.

In case of the Intercity to Brussels NS owns almost all of the sets of carriages. The NMBS provides one set of carriages to account for a shortage of available NS carriages. The ownership of the locomotives used for this train service is divided between NS and NMBS. In case of the lower speed Intercity's to Germany the carriages used are owned by DB. NS provides a locomotive to operate the service to the German border, after which a DB locomotive operates the remainder of the route. In general NS is only responsible for the maintenance of the trains it owns, but arrangements can be made to maintain all trains that end service in the operator's area. This is especially relevant concerning the stricter regulations for technical checks for international trains. NS does provide internal cleaning for all international trains that end service in the Netherlands.

Table 3 provides an overview of the characteristics of the intercity trains in the fleet of NS.

Table 3: Characteristics of International trains

	AMOUNT IN FLEET	**LENGTH**	**CARRIAGES (+ LOCOMOTIVES)**	**AVERAGE LENGTH CARRIAGE**
ICR_BLX (BELGIUM)	13	176.4	6 (+1)	25.2
ICR_DB (GERMANY)	0	255.2	9 (+1)	25.5
THALYS	2	200.0	10	20.0
ICE	3	200.0	8	25.0
EUROSTAR	0	390.2	16	24.4

2.3.4 Service requirements per train type

Different train types have different service requirements. The main differences in service requirements between train types are the frequency at which certain tasks have to be done and the duration of these tasks. Appendix 2 provides an overview of the service requirements of the train types of NS. The duration of tasks is provided given a standard crew if applicable.

The servicing requirements regarding internal cleaning of trains does not depend on the type of train, but it does depend on the type of train service this train operates. All trains operating solely in the Netherlands have to be cleaned once every day. In some cases some basic cleaning is conducted at terminus stations, but this has no influence of the servicing process at stabling yards. International trains however are often cleaned thoroughly between every service. The main reasons for this are the presence of catering services on these trains and the higher expectations of passengers regarding the cleanliness of these trains. The duration of the internal cleaning does depend on the train type. It is often presented as amount of minutes per carriage, so for longer trains internal cleaning takes longer. Double-decker trains have more floor space and more seats per carriage, so internal cleaning takes longer for these types of trains. Trains that are equipped with one or more toilets will also take longer to clean.

The frequency of exterior cleaning of trains does not depend on the type of train. All NS trains should be washed with soap once every seven days and with oxalic acid once every 63 days. The type of train does not directly influence the duration of this task. The length of a train unit does influence the duration of this task, as trains have to drive through the washing machine at a constant low speed. The general rule of thumb for the duration of exterior cleaning used by NedTrain is that cleaning of the two heads of the train takes 7 to 10 minutes per head (depending on the type of washing machine) and 1 minute per carriage. If trains are washed with oxalic acid instead of soap the duration increases to 4 minutes per carriage. At a few locations higher speed washing machines are used, which can realize a lower duration per carriage.

The frequency of technical checks does depend on the train type. Most trains that operate on the main Dutch network have to receive a B-check every other day and an A-check every twelve days. Exceptions to these frequencies are made for older trains, recently introduced trains and fault-sensitive trains. The frequency of the checks can be increased for these train types. Trains that operate international services or services on the high-speed line have to be fully checked every 24 hours. The duration of the technical checks is strongly dependent on the train type. For certain train types the checks of the cabin systems takes longer than for others. The checks of the state of the wheelsets and the interior takes longer for longer trains. Interior checks also take longer per carriage for double-decker trains.

Within the shunting and composing component of the servicing process there are several tasks that have a standard duration used by NedTrain. Coupling of train units takes on average 3 minutes, while separating units takes about 2 minutes. This does not depend on the type of train. A change of direction of a train does depend on the type. The engineer spends about 2 to 8 minutes in each of the cabins on either end. The time it takes to prepare the onboard systems of the train for the change of direction depends on the train type. The engineer also has to walk to the other end of the train, which is estimated by assuming an engineer walks at 4 km/h. Shunting movements do not depend on the train type, since the maximum speeds on stabling yards is very low. The duration only depends on the length of the train and the distance it has to cover.

2.4 Planning at stabling yards

There is no standard procedure that has to be followed in the stabling process. A standard planning is available for all stabling yards, but variability in the daily train circulation causes significant alterations to the schedule. This paragraph describes how the planning is made for a stabling yard, which forms of variability that affect the schedule exist and how planners cope with this variability.

2.4.1 Planning

NS uses a standard schedule for its daily operations. This schedule is valid for one year. After this year a new schedule is created, which is not always significantly different from the previous schedule. This schedule is created in collaboration with ProRail well before the start of the new year. A standard schedule is created for a week. This way small changes can be made for different days of the week, depending on passenger numbers. For example in the weekends on some corridors there are less trains, while on Friday and Saturday evening trains might continue to run longer. The length of the trains can also differ on different days of the week, so that NS can optimally respond to passenger demand.

For stabling yards a similar weekly schedule is created. This schedule contains the arrival time and composition of trains for each stabling yard, as well as the departure time and composition. The schedule also includes a plan to assign incoming train units to departing ones. The plan also includes a planning for standard service tasks, a parking location and all shunting movements required to get the train to the designated tracks. The schedule does not include specific train units, because of the uncertainty of the arrival of specific units caused by adaptations in the operating schedule caused by disruptions. This means that certain tasks cannot be planned beforehand. Exterior cleaning is a good example of this, because trains only have to be washed once every week. This means that on some days a lot more trains have to be washed than on others.

An update to the schedule is made one day in advance. The actual train circulation plan of NS is known at that point. A definitive schedule for the stabling yard is made only several hours before the end of the evening rush hour on the day itself. At this point the specific train units that will have to be serviced at the location are relatively certain. Due to the fact that variability in the circulation plan of NS is still possible, this schedule will not prove to be fully accurate. It will however not be updated anymore. Planners will make last-minute decisions to accommodate the required movements for the trains that actually arrive. They also plan the required shunting movements of trains that could not be planned in advance on the moment the need for this movement becomes clear. This can lead to inefficiency, as an ad-hoc made plan is not likely to be optimal. Trains cannot be moved until it is authorized, and the route might not be available anymore at that time.

2.4.2 Variability

In practice personnel of stabling yards often deviate from the provided schedule. The main reason for this is the unexpected nature of the arrival of the trains. During the day a lot of things can happen that cause a specific train unit to deviate from its schedule. This is mainly caused by disruptions that result in delayed and/or cancelled trains. Trains might short-turn if the corridor ahead is blocked or only allows limited operations. In case of significant delays of a train traffic controllers can also choose to insert a train unit on standby to operate the last part of a trip instead of the delayed train unit. The delayed train unit will become the unit on standby. Because significant disruptions are far from a rarity in the Netherlands, a significant portion of the train units exits active service at a different location than scheduled.

The variability could have several effects on the planning of the service process. There might be more or fewer trains that have to be serviced at the stabling yard, mostly caused by disruptions during the day. Trains could also arrive later than planned due to delays. Another form of variability is a different composition than planned. This could have already started in the morning, because of the correct train unit not ending up at the correct yard. This leads to a different composition in the morning. Train units could also have been swapped during the day for several reasons, such a mechanical failure or a disruption. The service requirements and planned repairs differ for each train unit, so more tasks might have to be performed than planned. This makes planning at stabling yards very difficult, resulting in controllers making last-minute changes. It could happen that not all tasks can be performed. A visit to the washing machine is often the first task that is skipped on busy nights.

2.5 Stabling capacity

The capacity of a stabling yard is defined as the maximum amount of trains that can be stabled at the yard. It can be given in amount of trains, amount of carriages or meters. Providing the capacity in amount of carriages is most commonly used in the Netherlands, although the introduction of new trains with substantially shorter carriages might cause a shift towards a capacity in meters in the near future.

In the current stabling process, the capacity of a stabling yard consists of three main components: the physical stabling capacity, servicing capacity and shunting capacity. Each component has its own capacity. The total capacity of a stabling yard is the lowest capacity of these three components. Because there are several stabling yards in the Dutch rail network a shortage in capacity of one component can be compensated at a different location. This does however lead to significant empty train movements between locations, which is a serious expense for NS. It should therefore be avoided as much as possible.

2.5.1 Physical stabling capacity

The physical capacity of a stabling yard relates to the amount of trains that can be parked at a service location. It is often estimated as the sum of the effective lengths of all tracks, diminished by a certain loss factor due to the fact that trains are never parked 100% accurately (in Dutch: versnijdingsverlies). In the Netherlands this factor is usually set at 7%. The effective length of a stabling track is the length at which trains can be parked. Switches and signals are never part of the effective length, and crossings for personnel are usually also kept free of trains. The total physical capacity of a stabling yard consists of the effective length of all dedicated stabling tracks, as well as the additional capacity on the yard and platform capacity. Additional capacity can for example be obtained by parking trains on servicing tracks (in case of a carousel servicing process) or shunting tracks after these tasks are completed for all trains. Platform capacity is obtained by moving the trains first operating a train service in the morning directly to the platform after servicing. Additional capacity can also be obtained by parking trains at a different location after servicing. This way locations that do not have facilities for servicing trains can also provide stabling capacity. This does however lead to empty train movements.

2.5.2 Servicing capacity

The servicing capacity relates to the amount of trains that can be serviced. It depends on many factors, such as the amount and length of tracks, amount of available facilities, amount of personnel, train types and service level. The service level mainly determines the frequency in which certain tasks are performed. If tasks are performed more often trains spend on average more time on a servicing track, which decreases the capacity. This is assuming the amount of personnel remains constant. If the amount of personnel is increased the time a train spends at a servicing track can be decreased, which increases capacity. The train schedule has a significant effect on the servicing capacity. Different types of trains have different servicing requirements, which is expressed in the duration. Double deck trains take a lot longer to clean internally compared to single deck trains, for example. Technical checks are often more thorough on older trains, increasing the duration.

2.5.3 Shunting capacity

The shunting capacity in relation to stabling capacity can be defined as the maximum amount of trains that can be moved on the yard in order to meet the requirements of the stabling process. It relates to the occupation of the available infrastructure on a stabling yard. The shunting capacity could be limited by the unavoidable intensive use of one or more switches or tracks where trains have to change direction. This could especially be a constraint to capacity on large stabling yards with a shuffleboard layout, one central switch complex and a carousel servicing process, such as Amersfoort Bokkeduinen. Another possible cause for a limited shunting capacity is the need to cross active tracks. If a carousel servicing process is used on a stabling yard that is divided into several parts separated by active tracks, there might not be enough gaps in the schedule to cross these tracks. This could for example be the case in Rotterdam, if a carousel servicing process was used there.

2.5.4 Limitations to use of capacity

The usable capacity of a stabling yard can also be reduced by influences outside of the yard itself. Enough trains have to be able to reach the stabling yard in order to be able to fully use the capacity. If there are fewer trains leaving active service near the stabling yard than there is capacity, trains would have to be brought in from other locations. This is a significant cost component, so it is only done if there are no other options. The infrastructure outside the stabling yard can also be a limiting factor. A prime example of this is Utrecht Cartesiusweg. Currently only about two thirds of the capacity is used, because the yard is only directly accessible from a few of the platform tracks at Utrecht Centraal. Complicated shunting movements are required to get more trains to the yard, which is currently not feasible. Stabling yards also have an environmental capacity. Agreements are made with municipalities about the maximum noise production from a yard that NedTrain has to stay within. Environmental capacity is not assessed in this study.

2.6 Conclusions

In the Netherlands 33 service locations exist. NedTrain is responsible for the servicing of trains at these locations. As a subsidiary of NS, it mainly services their trains, although other operators can also request NedTrain to service their trains. ProRail is responsible for all infrastructure in the Netherlands, including the tracks at service locations. ProRail provides construction and maintenance of infrastructure, as well as dividing capacity on the tracks and stabling yards to operators.

Service locations can have a carousel or shuffleboard layout. A shuffleboard features mainly dead-end tracks, while a carousel stabling yard has a central switch complex on both sides. Two servicing types exist: low servicing and carousel servicing. With low servicing trains are parked and cleaned on the same track, while personnel moves from train to train. With carousel servicing these two tasks are separated, so trains move from servicing to stabling tracks while personnel stays at the servicing tracks.

Five main tasks are performed at stabling yards: exterior cleaning, interior cleaning, technical checks, repairs, and shunting and composing of trains. Each task has to be performed with a certain frequency. This frequency can differ between train types. The time tasks take can also differ between train types. In total NS has 14 different types of trains that require servicing, with several of those consisting of two subtypes.

A standard weekly planning is made for stabling yards one year in advance. The amount of trains that has to be serviced in a night is then roughly known. The final schedule is made only a few hours before the end of service. This is due to the variability in the arrival process of the trains, mainly caused by disruptions on the network. The exact service needs are therefore known very late, causing planners to make part of the planning when the movement is requested. This leads to inefficiencies in the overall service process.

The capacity of a stabling yard has several components: the physical stabling capacity, servicing capacity and shunting capacity. The actual capacity of a stabling yard is the lowest of these three components. The capacity can be further limited by limitations in the accessibility of the yard and the environmental capacity. The schedule of NS can also limit the amount of trains that can reach the stabling yard, which can lead to a higher capacity than is needed.

3 The 100 percent servicing concept

In this chapter the 100% servicing concept will be described. First the main goals of this concept are presented in chapter 3.1. Chapter 3.2 elaborates the development of 100% servicing. A description is given of the main causes that lead to this concept, as well as the programs and concepts used as inspiration. In chapter 3.3 the general characteristics of 100% servicing are presented. This paragraph also describes the characteristics of service locations that could influence the 100% servicing process in chapter 3.4. In chapter 3.5 potential factors associated with 100% servicing that could influence the capacity are described.

Since 100% servicing is a new concept very limited literature is available. The information presented in this chapter has been obtained during personal visits to NedTrain service locations in Zwolle and Amsterdam Watergraafsmeer. In Zwolle Henk Kuper from NS has provided a tour of the location and a presentation on 100% servicing. In the Watergraafsmeer Alex Mulder from NS provided a presentation on 100% servicing. In both instances personal questions about 100% servicing have been answered as well.

3.1 Main goals of 100% servicing

The main incentive for the development of the 100% servicing concept is the upcoming midterm review of the overall performance of NS in 2019. This midterm review will be part of the assessment made by the ministry of Infrastructure and Environment (I&M) in 2024 whether or not the concession for the main rail network in the Netherlands will be given to NS again (Ministerie van Infrastructuur en Milieu, 2015). An important part of the midterm review is the assessment of the performance of NS by its passengers. Surveys will be taken amongst passengers to determine the grade they would give the performance of NS. The goal that has been set for NS is that at least 80% of the passengers give a grade of 7 or above on a scale of 1 to 10 for the overall performance of NS (NS, 2016). Meeting this goal will contribute to the chances of NS to keep the concession of the main rail network after 2024.

In the surveys for the midterm review passengers will provide grades for the performance of NS for different categories. These categories include among other things the punctuality of trains, the chance of finding a seat in a train, the cleanliness of the train, passenger comfort and the overall service provided. Improvements in the servicing process of trains can have a positive influence on all abovementioned categories. The cleanliness of trains can be improved by cleaning trains more often and more thoroughly. Passenger comfort can be increased by ensuring there are fewer defects in the interior of the trains, such as ripped seat covers or broken air-conditioning units. The punctuality of trains in the morning rush hour can be improved by ensuring more trains leave the stabling yards on time. The chance of a passenger finding a seat in a train might be improved slightly by ensuring less trains are taken out of active service because of the need for repairs by finding technical faults earlier and repairing them as quickly as possible. All these improvements combined can also influence the assessment of the overall service provided by NS. The main goal of 100% servicing is therefore to increase passenger satisfaction by improving the quality of trains.

To increase the quality of trains changes have to be made to the service process. Tasks related to improving the quality have to be performed more frequently and/or more thoroughly. However, during the development of the concept it became clear that in order to be able to reach this goal, additional efforts were required. The stabling process would have to become more efficient in order to keep the stabling capacity at a constant level. As a result the goal to improve the efficiency of the process is added to the goals. In the last couple of years the pressure on the overall stabling capacity within the network has significantly increased due to the expansion of the fleet of NS. Since the fleet expansion will continue over the next couple of years, ProRail and NS are under pressure to find additional stabling capacity within the existing infrastructure. If the efficiency of the stabling process becomes high enough, it is possible to increase the capacity of a stabling yard without building expensive and time-consuming new infrastructure. Therefore the goal to increase the stabling capacity is added to the goals of 100% servicing. The increase of the quality and punctuality of trains will however remain the main goal of 100% servicing.

3.2 Development of 100% servicing

The 100% servicing concept is not the first concept that aims to improve certain elements of the general servicing process that have influence on the key performance indicators. In the first half of 2016 NS introduced the Pitstop strategy (NS, 2016). This program aims to reduce the time trains have to be withdrawn from service as a result of unexpected technical malfunctions. This results in a lower amount of trains being withdrawn from service simultaneously. This way a higher amount of trains can be used in the rush hours, which increases the amount of available seats and therefore passenger comfort. The higher amount of available trains can also be used to increase the active reserve, so train units with a defect or large delay can be swapped more easily.

Another recently introduced program is the 4J-approach (NS, 2016). This program aims to ensure the right train is at the right location at the right moment with the right quality. One aspect of this program is to increase the amount of trains that leave active service in the evening at the correct location and in the correct composition, which makes ensuring trains leave in the correct composition in the morning easier. Better planning of movements on stabling yards has to result in a higher amount of trains that can be properly cleaned on time and leave the stabling yard on time. 100% servicing in essence is an evolution of the 4J-approach.

The 100% servicing concept features elements of the Lean Six Sigma concept. Lean Six Sigma is a methodology that combines the Lean manufacturing method and the Six Sigma techniques to improve performance by removing waste and reducing variation (Pepper & Spedding, 2010). Lean manufacturing identifies three types of waste: muda (non-value-adding work), muri (overburden) and mura (unevenness). A relevant example of non-value-adding work is the movement of people or equipment. Six Sigma is a set of techniques that aim to improve the quality of the output of a process by removing causes of defects and minimizing variability. In the servicing process a lot of variability exists, because the service demands for train units can differ significantly. This makes planning tasks difficult. The 100% servicing concept mainly adopts the aim from Lean Six Sigma to provide a smooth process flow by removing waste and removing the variation caused by work scheduling.

The 100% servicing concept was first developed for the stabling yards in Zwolle by a team led by Henk Kuper. The need for additional stabling capacity has increased in the last couple of years. In Zwolle two stabling yards exist: Zwolle RGS on the west side of the station and Zwolle Oosterhaven on the east side. Both of these locations are used to service and park trains of NS. Both locations are operated from a NedTrain location at Zwolle Oosterhaven. This means that for the work on trains to be done at location RGS, personnel and in some cases also equipment has to come from the other location. Personnel could be travelling from one location to the other several times per night. Furthermore, the organization of the servicing process at Zwolle RGS causes a lot of inefficiency. Complicated shunting movements could be necessary in order to get all trains during a night shift at one of the tracks equipped to service trains. In total a lot of waste in the process can be identified, which leads to a low productivity.

In order to improve the quality of the trains more tasks will have to be performed. In Zwolle they realized that in order to be able to facilitate these additional tasks without it resulting in a lower stabling capacity, drastic changes would have to be made. Either the size of the stabling yards would have to be increased by constructing new tracks, or the inefficiencies would have to be removed from the process. Because increasing the size of a stabling yard is a very costly and time-consuming affair, the choice was made to explore options to increase the efficiency.

The first realization in Zwolle was that operating two stabling yards side by side is very inefficient. Furthermore, only Zwolle Oosterhaven is equipped with a washing machine, which is a complication if you want to improve the quality of the exterior of the trains. The idea arose to concentrate all servicing tasks at one location and only use the other location exclusively to park trains. Since Zwolle Oosterhaven has a washing machine and other facilities, the choice was made to service the trains here and park the trains at Zwolle RGS after servicing them. With stabling trains being the only task performed at RGS, the available infrastructure can be optimally used for this. No tracks have to be reserved for shunting movements to reach servicing tracks. One condition is that trains are parked according to the LIFO (Last in First Out) principle, so they don’t block each other in the morning.

The separation of the servicing and stabling of trains causes a flow of trains from one location to the other. The amount of tracks at location Oosterhaven that can be used to clean trains is limited, so several trains have to use the same track after one another. The same goes for the washing machine, of which one is present. This also creates a flow of trains through the servicing location. The service demand of each train is different, which can cause a large variation in the required time a train has to spend at a servicing track. In Zwolle they realized that these large variations complicate the flow of trains and makes planning difficult, which leads to more inefficiencies. Therefore the choice was made to create a constant flow. The time trains spend at the servicing tracks is standardized. In the case a train cannot be fully serviced in this time, it is removed from the main flow and the remaining servicing tasks are performed at a dedicated location where the flow of the process is not affected.

3.3 Characteristics of 100% servicing

The 100% servicing concept features some characteristics that differ from the current service process. For each train the process is standardized into several steps all trains have to undergo. The introduction of the takt time makes the planning of movements significantly easier.

3.3.1 Process steps

As described in the previous chapter, the 100% servicing concept focusses on the separation of servicing and stabling and a constant flow of trains between the different locations dedicated to certain tasks of the process. The variation in the tasks each train has to undergo is removed from the process as much as possible. The general setup of the 100% servicing process is divided into eight steps. All trains go through these steps in the given order. However, certain aspects of the available infrastructure on a location may result in a combination of steps 4 and 5 into one step or a change in the order of the process steps. In Zwolle the eight steps have been formulated as follows:

1) Exit from active service. After unloading the last passengers at the final station the train will drive towards the stabling yard.
2) Buffering and composing of trains. In this location trains will wait until they can enter the servicing process. Additionally, trains can be separated and combined here if necessary to compose the trains in the correct order for the entry into service at the end of the process.
3) Servicing part 1: exterior cleaning. The trains will drive through a washing machine (TWI) to clean the exterior. Trains are usually washed with soap, but can be washed with oxalic acid if the deadline approaches or the train is exceptionally dirty.

4) Servicing part 2: interior cleaning, inspections and repairs part 1. In this part the technical checks are completed and a start is made with repairs.
5) Servicing part 3: interior cleaning, inspections and repairs part 2. In this part the train is cleaned internally and the remainder of the repairs is conducted.
6) Servicing part 3a: Additional service (optional). In the event that a train has more work to be done on it than is possible in the given time frame for the other servicing steps it will be taken to a separate track to finish servicing without interrupting the flow of the process.
7) Stabling of trains. Trains will be shunted to stabling tracks. These tracks can be located at the stabling yard itself, but it is also possible that trains are parked at platform tracks or on other locations. Another option is for a train to directly enter active service after being serviced.
8) Entry into service. The trains will drive from the stabling yard to the first station to start active service if applicable.

Figure 4 shows the layout of the stabling yard in Zwolle with the location of the different steps of the process. It can be seen that step 4 and 5 are performed at the same location. The trains do not move between these two steps. This could be different for other stabling yards. It mainly depends on the infrastructure layout whether it is beneficial to combine the two steps.

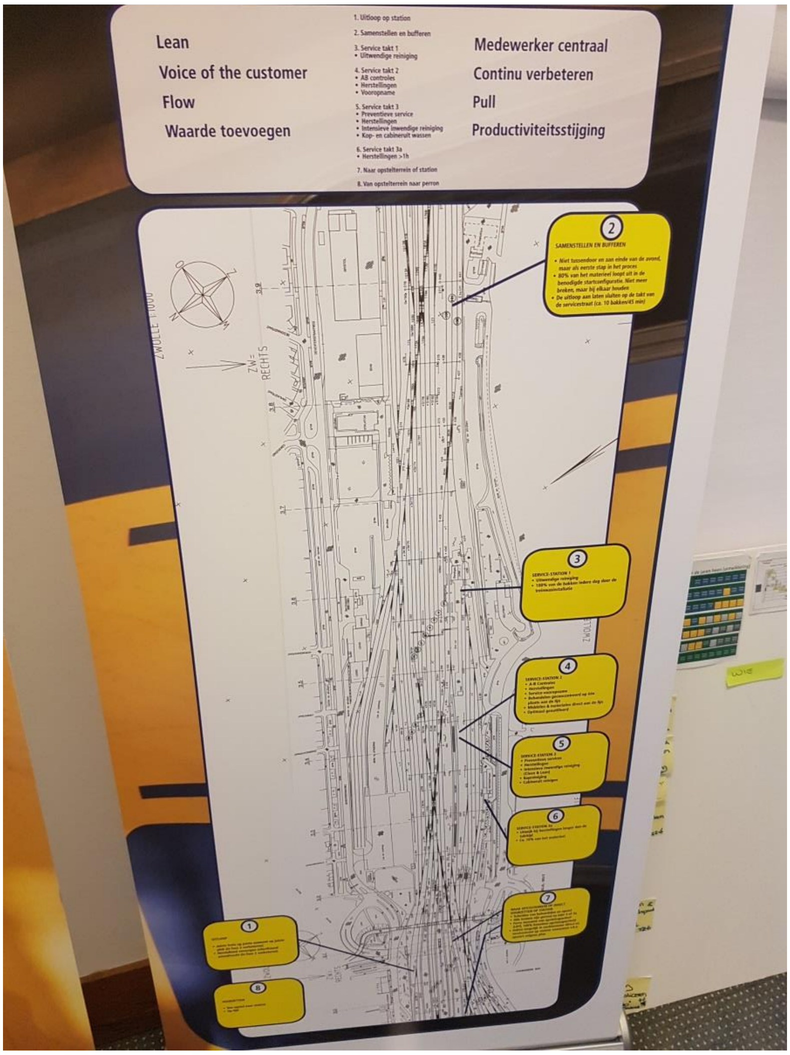

Figure 4: Overview of locations of steps in Zwolle

3.3.2 Main differences with current service process

The main differences between the current service process and 100% servicing are the execution of additional servicing tasks, the frequency increase of certain tasks and the standardized flow of trains through the stabling yard. The largest differences would occur on stabling yards where currently low servicing is used. At these locations trains are now parked on a stabling track and all tasks are performed at this location. The train only moves during the process if it has to visit the washing machine or aerial platform for example. On stabling yards where currently a carousel servicing process is used the differences are much smaller, as trains were already moving around on the yard. Here the only difference will be the standardization of the movements and time a train spends at a servicing track, besides the increase in frequency of tasks.

The task that undergoes the largest increase in frequency compared to the current stabling process is exterior cleaning. Trains are currently only washed if the seven day interval has been reached and there is capacity available on the yard to facilitate this. With 100% servicing trains will go through the washing machine every day to be washed with soap. The interval for washing with oxalic acid is not increased. The state of the trains is also checked more frequently. The frequency of the A- and B-checks is not increased, but the interior of trains is checked more frequently. Especially systems that are currently not checked regularly or not very often, such as the air conditioning, heating, intercom, interior lighting and electrical sockets (if applicable), will be checked daily. Furthermore, more time is scheduled to perform simple repairs on electrical systems and the interior of trains and more replacement parts will be kept in storage.

3.3.3 Takt time

An important element of 100% servicing is the takt time. This is the standardized time that trains spend at different steps of the process. It is most common to base the takt time on the steps that take place on a track with a servicing platform, because it has to be chosen in such a way that a large enough percentage of trains can be fully serviced on time. The takt time has to be carefully chosen for each location. It depends on the available infrastructure, facilities and personnel available, as well as the composition of trains that have to be serviced. The main factor is the amount of carriages a standard crew can service within the takt time. This should match the total length of the service tracks to fully optimize capacity. One train can be moved while personnel services the train on the other side of the platform. The length of the service tracks compared to the trains plays a role. The choice can be made to service two short trains behind one another if the track is long enough.

At the moment the choice for takt time is based on a rough estimate. In Zwolle a takt time of 90 minutes has been chosen for the servicing of trains. It is estimated that 92% of trains can be fully serviced on time. There are however plans to increase this time to 120 minutes to improve efficiency for personnel requirements. It is thought that this will improve the process, but there is no real scientific basis for this change. At Amsterdam Watergraafsmeer however, the plan is to start the test with 100% servicing with a takt time 60 minutes. The main difference between Watergraafsmeer and Zwolle with regard to infrastructure layout is the large amount of servicing tracks compared to the overall size of the yard. This might contribute to the choice for a lower takt time.

3.4 Layout characteristics in relation to 100% servicing

The optimal design of a stabling yard to accommodate 100% servicing focusses strongly on the smooth flow of trains. Shunting movements of trains are necessary to follow the main principle to increase efficiency. The shunting movements themselves however represent a waste in the process, as they are not part of the necessary tasks. The optimal design of a stabling yard therefore minimizes the duration and length of shunting movements. Two main components of shunting movements have a negative influence on the duration of a shunting movement. The first is a change of the direction of movement of the train. The driver will have to walk from one side of the train to the other and also has to implement the change of the cabin used into the computers of the train. Depending on the length of the train this can take 5 to 10 minutes. If a train is composed of carriages pulled by a single locomotive the duration of the direction change might be considerably longer, as the locomotive has to be disconnected, drive to the other side of the carriages (for which at least two direction changes of the locomotive are required) and reconnect to the carriages. This type of train is in the Netherlands however quite rare, so this problem is limited.

The duration of shunting movements can also be negatively affected by the intended occupation of one piece of track by more than one train at the same moment. Trains might have to wait for another train to pass by before it can commence the shunting movement. Shunting movements that require a direction change are more susceptible for this, since the duration of the movement is longer. The track at which this direction change is carried out will also be occupied for about 5 to 10 minutes, which prohibits other trains from using this track. In some cases a shunting yard is separated into two or more locations that are separated by mainline tracks. These tracks can be used for the operation of passenger or freight services. These trains are usually given priority over shunting movements. Shunting trains might have to let several trains pass before they can continue their shunting movement, which can significantly lengthen the duration of a shunting movement. The location in the Netherlands where this problem is most present is Rotterdam. This stabling yard is divided into four locations, all separated by mainline tracks. Figure 5 shows the layout of stabling yard Rotterdam. The dotted lines indicate tracks that are not included in the railway safety system. Stabling tracks can be included in the safety system, but often they are not. In Figure 5 all dotted lines represent stabling tracks and all continuous lines represent mainline tracks.

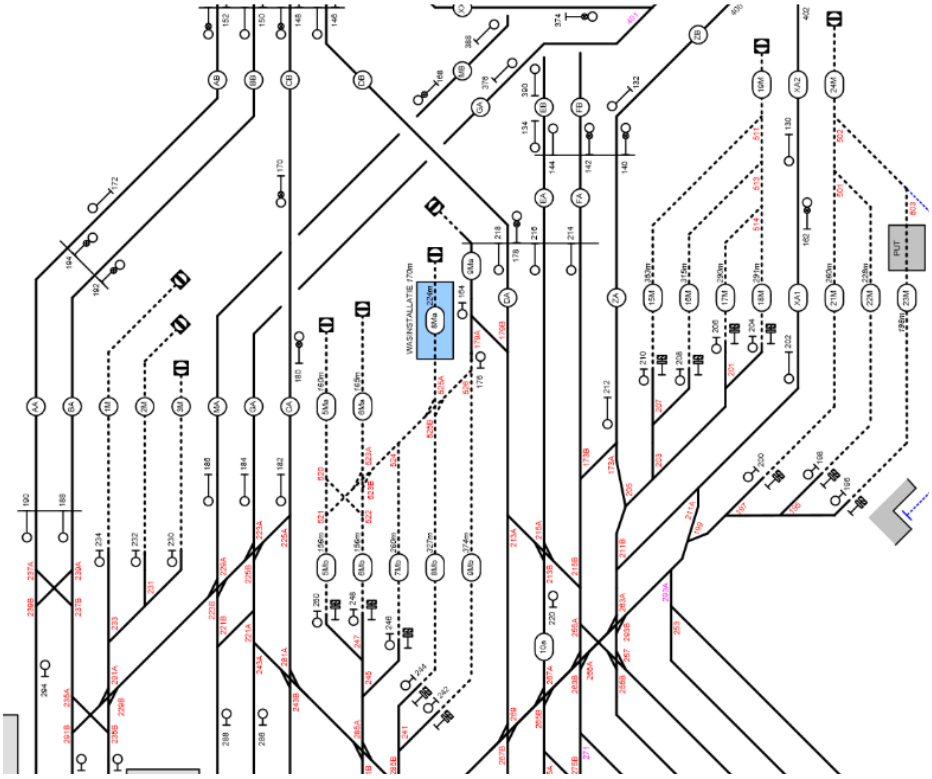

Figure 5: Schematic overview of the stabling yard in Rotterdam (Zeegers, 2017)

An example of a stabling yard that is suitable for efficient implementation of 100% servicing is Lelystad Opstelterrein. It is a stabling yard with a carousel layout type. It has been constructed quite recently and was never intended for any other use such as shunting freight cars. At this location stabling and servicing are mostly separated and servicing is done with a carousel process. Figure 6 shows the schematic layout of Lelystad Opstelterrein. Currently a carousel service process is used here. It is not difficult to imagine 100% servicing being implemented here. Trains enter the yard on track FL. Tracks 6 to 8 can be used as buffer, after which trains can go to the TWI via track 24. Then the TWI trains change direction and are serviced at track 22 or 23. Track 21 can be used for incidental additional servicing. Trains are subsequently parked at track 2 to 5 and, when most trains have arrived, tracks 6 and 7 can also be used to park trains. The last trains that are serviced in the night shift can remain on the servicing tracks until the time of departure. Trains leave the yard via track FW. Tracks 8 and 24 would be dedicated shunting tracks.

The layout is however not optimal. The change of direction at the TWI increases the duration of this step, reducing its capacity. It also causes some switches to be used by trains moving in different directions, which could result in trains having to wait on another train to conduct the required shunting movement. The track that seems most suitable for additional servicing for trains that require more time than the chosen takt time can only be reached with a movement that includes a change of direction. This increases the shunting time, but it also requires one of the stabling- or buffer tracks to be empty, which can cost capacity or hinder other movements.

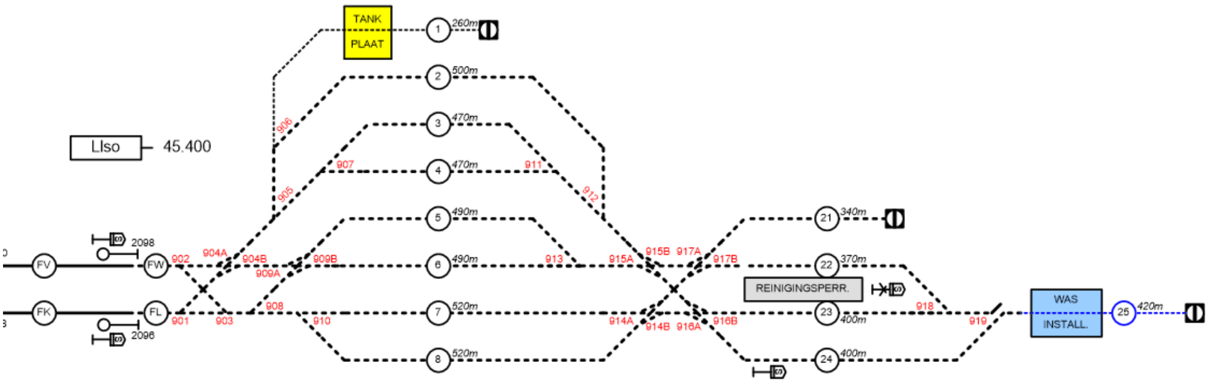

Figure 6: Schematic overview of the stabling yard in Lelystad (Zeegers, 2017)

3.5 Effect of 100% servicing on stabling capacity

The fact that extra servicing tasks will be performed and the frequency of other tasks is increased logically seems to cause a reduction in stabling capacity. Personnel would have to perform more tasks, which would reduce the amount of trains that can be serviced in a certain timeframe. There are however several aspects of 100% servicing that could lead to an increase of capacity.

3.5.1 Capacity increase through separation of servicing and stabling

The separation of stabling and servicing mainly has an effect on the physical stabling capacity. Compared to low servicing trains do not have to be parked on tracks that are equipped with facilities that allow servicing of trains. On some stabling yards this means that more tracks can be used to park trains, increasing the stabling capacity. The fact that trains are fully serviced before they are parked can also lead to a lower required shunting capacity. In the current service process it is not uncommon for a train to go to the washing machine after it is parked. Tracks would have to be kept free to allow this movement. With the separation of servicing and stabling these tracks can also be used to park trains.

The benefits from the separation of servicing and stabling are heavily dependent on the specific location where this is applied. On locations that use a carousel servicing process the benefits are likely lower compared to low servicing. On some stabling yards servicing and stabling are already mostly separated. Especially on a stabling yard like Lelystad Opstelterrein, which has a layout that is very suitable for an efficient carousel process, the benefits could be zero.

3.5.2 Capacity increase through simplification of planning

The simplification of the planning of movements of trains on a stabling yard can lead to a decrease of inefficiency in the process. In the current situation it is never accurately known how long a train will spend at a service track. With the introduction of the takt time this is known, so the planning can be followed much more accurately. Movements of trains can be planned more in advance, which can lead to a more optimal shunting plan. In the current situation the moment a train is ready to be moved is much more uncertain. This makes the assignment of shunting drivers more difficult. Moves also has to be approved by the planner. Both these things can delay the movement of a train from the moment it is ready, reducing efficiency and therefore potentially capacity. The standard route trains follow through the process also makes planning easier. Some additional inefficiency is however created by standardizing the duration of tasks for all trains. They will for example stay at a service track until the planned moment of departure, even if they are ready before that moment. This can be seen as a reduction of service capacity, although the service capacity also depends on other factors.

3.5.3 Potential causes for capacity reduction

There are also some aspects of 100% servicing that can lead to a lower capacity. Because some tasks are performed more often with 100% servicing, more personnel might be needed to maintain the same capacity level. If this is not increased the service capacity could be reduced. This is especially true for mechanics, which would have to conduct more checks. For internal cleaning it is possible that less personnel is needed. Their tasks aren't changed much, but the separation of servicing and stabling could lead to a reduction of the time spend walking. This would especially be a large benefit on a location such as Zwolle, which operates two locations from one central point.

The increase of the frequency of certain tasks with 100% servicing can also lead to a reduction of capacity in other ways. An example of this is the washing machines. With 100% servicing there will be a large increase in the demand for the TWI. If the TWI can't handle the amount of trains being serviced with the current service process, the capacity is reduced. The capacity could also be reduced by the increased need for shunting movements. If the infrastructure can't support this increase, the shunting capacity can become lower than the original capacity of the stabling yard. This is especially true for stabling yards which currently use low servicing, which are also mostly stabling yards with a shuffleboard layout. These yards often have one central switch complex, which combined with the need for saw movements can see a significant increase in demand.

The design of the servicing process as an assembly line can also have an effect on the flexibility of the process. If one component of the process 'breaks down', the whole process can grind to a hold. An example would be a failure of an important switch which has to be passed to get from the TWI to the servicing platforms or a broken down train that cannot be moved on time. The flexibility of the process could be increased by assuring there is a route to bypass potential critical elements of the infrastructure, but this will require a larger amount of track dedicated for shunting movements, potentially reducing stabling capacity.

3.6 Conclusions

The main goal of the 100% servicing concept is to increase the passenger appreciation of NS through the cleanliness of the trains. Achieving a high enough passenger appreciation in several reviews conducted by the ministry of Infrastructure and Environment is part of the decision to grant the concession to operate trains on the main rail network in the Netherlands to NS again in 2025. The goal to increase the capacity of a stabling yard with 100% servicing has been added later when the concept was being developed.

The 100% servicing concept is an evolution of the Pitstop strategy and the 4J-approach of NS. It also uses elements of the Lean Six Sigma methodology to remove waste from the process. The concept was first developed in Zwolle, where the side-by-side operation of two adjacent service locations causes significant inefficiencies, especially regarding the productivity of personnel. They realized that using one of the two locations exclusively for stabling trains and the other for all servicing tasks could lead to the increase in capacity needed to facilitate the additional servicing tasks required to increase the quality of the trains, and potentially even increase the stabling capacity.

The servicing process with 100% servicing is divided into eight steps. The exact shape of the process can differ between locations due to limitations in the infrastructure layout. The main difference with the current service process is the increase of frequency of tasks that directly influence passenger comfort, such as exterior cleaning and checks and repairs of all elements of the interior of trains. Another important difference is the structure of the process as an upgraded carousel process with a standard duration of process steps: the takt time.

The layout characteristics of a stabling yard can have an influence on the 100% servicing process. Yards with one central switch complex that has to be used intensively and yards with main tracks running through them are likely to be less efficient due to the planning of shunting movements being more difficult. Yards that can feature all steps behind one another, eliminating crossing movements of trains, can realize the most efficient process.

The 100% servicing concept can have a positive influence on the capacity of a stabling yard though the separation of stabling and servicing. Stabling can be done more efficiently if additional shunting movements are not necessary. The simplification of planning can also lead to more capacity. The increase in tasks performed and the potential need for more shunting movements could also cause a reduction of stabling capacity.

4 Model development

In this chapter the model developed in this study will be presented. Existing models for capacity analysis, shunting plans and train schedules are examined in chapter 4.1. In chapter 4.2 the model framework is outlined. This includes the output of the model. The required input to achieve this desired output is described in chapter 4.3. The steps that have to be taken to get the desired output from the input are described in chapter 4.4. This chapter also elaborates the validation of the model in chapter 4.5.

4.1 Models for stabling yards

The use of models and algorithms in the rail sector to determine capacity is not new. The earliest models were created to determine the capacity of line sections on main railway lines or to determine the capacity of a rail network. An overview of available literature on this topic until 1979 is given in (Assad, 1979). These types of models are also used to create train schedules and timetables. Abril et al. (2008) described in their article the main concepts and methods to perform capacity analyses. Three types of methods are described: analytical, optimization and simulation methods. An automated tool that is able to perform several capacity analyses is presented. It is focused at capacity analyses on track sections.

In (Zwaneveld, Kroon, Romeijn, & Salomon, 1996) a model is presented that focusses specifically on the routing of trains through railway stations. This model automatically generates and evaluates detailed timetables for station areas. In the paper a mathematical model formulation is presented based on the Node Packing Problem. Van den Broek and Kroon (2007) describe a model that tests at any moment during the planning process if the infra capacity between platform tracks and shunting areas is sufficient. This test reduces the need for a detailed plan well in advance. The test is based on a mixed integer programming model.

Models are also available for shunting purposes on stabling yards. Lentink (2006) describes a train unit shunting algorithm in his PhD thesis. He describes four subproblems of shunting capacity: the Train Matching Problem, Track Assignment Problem, Shunt Routing Problem and the Shunt Unit Cleaning Problem. He also describes an approach for integrating the matching and parking subproblems. One of the conclusions is that input from human planners will remain of importance. Di Stefano and Koci (2004) describe in their paper different methods for the arrangement of trains in the 'correct' order by avoiding shunting operations for outgoing trains. Both algorithmic solutions and heuristic approaches are proposed for this problem.

Van den Broek (2017) describes in his thesis report that he created a simulated annealing algorithm that evaluates all components of the shunt plan simultaneously. It uses an iterative process to improve the shunting plan. The activities on a stabling yard are modeled as nodes in a precedence graph. Tomii and Zhou (2000) regard shunting problems as resource constrained project scheduling problems. An algorithm is proposed for shunting problems combining genetic algorithm (GA) and Program Evaluation and Review Technique (PERT). This model determines the timings of tasks separately from the shunt plan using PERT.

NS is currently working on a model to determine the capacity of a stabling yard using a Pareto Front Analyser, as described by Hoepel (2017). This model creates daily schedules for shunting movements, from which the capacity can be derived. The analyser is multi-objective and finds an optimal solution balancing all objectives.

Janssens (2017) took a different approach to estimate the capacity of a stabling yard. He conducted an empirical analysis using data from all stabling yards in the Netherlands. The model estimates the capacity of a yard using data about: the layout type, number of tracks, presence of a washing machine, washing machine type, location of yard in network, mix of train types and expected number of work orders. These factors were determined to significantly impact stabling capacity.

Most of the models and methods presented in this chapter depend on a form of optimization in order to solve capacity problems. This is a method that is commonly used in practice, as optimized shunting plans are often created. Both optimization and simulation methods often require a specific schedule of arrival- and departure times of trains to accurately determine the shunting capacity of a stabling yard. As it is useful to know the capacity when creating a schedule, the capacity is often determined by assessing many schedules with different amounts of trains and different train types. This is a time-consuming process, making it not suitable for quick assessments of capacity. A quick assessment is possible with an analytical model, but these often lack accuracy as assumptions are needed to compensate for the lack of a known schedule. Furthermore, models that can incorporate specific servicing tasks are scarce. As 100% servicing is a new concept, no models were found that are specifically used for 100% servicing. The model in this study aims to be a simple analytical model with limited computational time that does take into account the characteristics of the 100% servicing process.

4.2 Model framework

The main goal of the model to be developed is to provide information about the capacity of a stabling yard with the implementation of 100% servicing. The model should be simple to use, by allowing a limited amount of adaptations necessary to change the stabling yard that is being assessed and taking a limited time to run the full model. It should also allow easy adaptations to the infrastructure layout and the service process characteristics in order to be able to compare different scenarios and assess the general effect of certain measures. The model should use general data that is available for all stabling yard in the Netherlands. The model should also be usable for stabling yards in other countries. If the model were to be used for this purpose, the input data obtained from this country should be converted to the same characteristics as the Dutch input data if necessary. Only limited changes to the model itself would be necessary.

The output of the model consists of an estimation of the capacity of a stabling yard, given the conditions provided. The capacity is presented in total amount of meters and in total amount of carriages. The capacity in carriages is presented using the standard carriage length of 27,2 meters used by NS and ProRail. This is the length of the longest carriage in the fleet, which ensures the calculated capacity can be reached. This can be changed for use in other countries. The model provides the capacity of different elements of the stabling process. The capacity of the washing machine(s), service tracks (both main and additional) and stabling tracks is determined, as well as the shunting capacity. This way the element that is the bottleneck in the service process can be determined. The final stabling capacity is calculated from the five elements. It is the lowest value of the five. Figure 7 highlights the framework of the model. The input data is elaborated in chapter 4.3. The capacity of the buffer tracks is determined separately for different sets of parameters, as it is unclear what the exact values of these parameters are. It is not included in the calculation of the final stabling capacity. These values can be compared with the other capacity values calculated by the model to provide insight in the likelihood that the buffer capacity is the biggest bottleneck. Adaptations to the infrastructure or the process can then be made to reduce this bottleneck and increase the total stabling capacity.

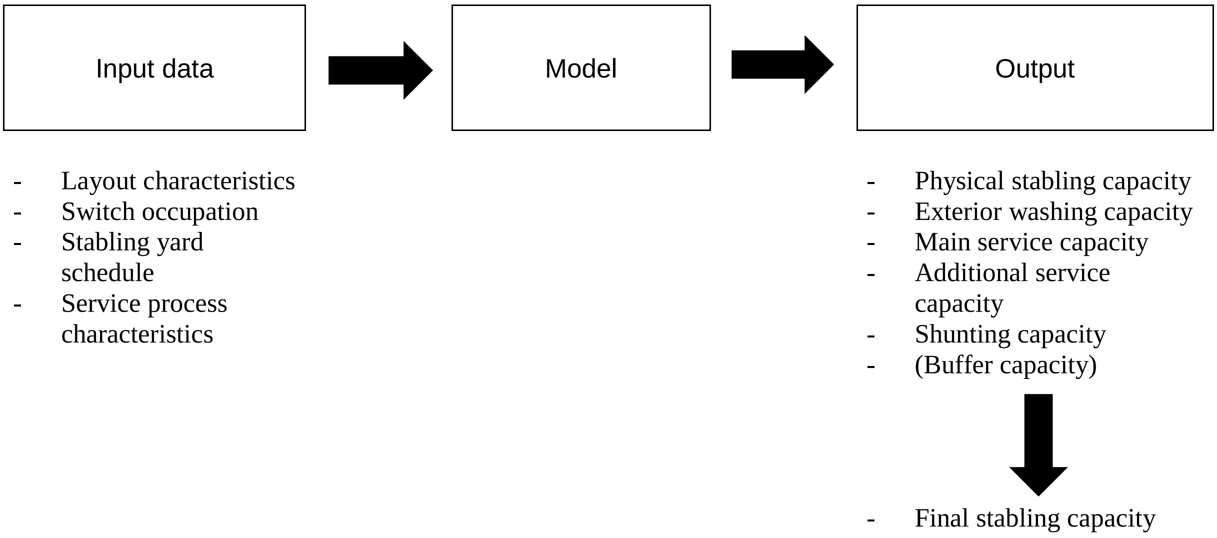

Figure 7: Model framework

The model is constructed as an analytical model, as described in (M. Abril, 2008). This type of model best matches the goal of this study to provide a simple and quick model. The capacity of a stabling yard is estimated with a set of formulas. These formulas are described in chapter 4.4. The model uses several assumptions in order to estimate the capacity, which has an influence on the accuracy of the model. The programming language Python has been selected to construct the model in, as this is a simple programming language that is better able to handle large datasets than software such as Microsoft Excel. Enthought Canopy is used to program the model in.

4.3 Model input

In order to be able to produce the model output, the necessary input data has to be collected. There are two types of data required as input for the model: location-specific data and general data related to the service process.

4.3.1 Location specific data

The main aspect of the location specific data is all necessary information concerning the layout of the stabling yard at this location. Data is needed on the layout characteristics of all tracks and switches present. A distinction is made between primary tracks and secondary tracks. Primary tracks are defined as tracks that have a name that is not related to other tracks it connects to, for example track 1 or track A4. They can have a distinctive function, such as platform track, stabling track or servicing track. Secondary tracks are defined as all tracks that connect two main infrastructure elements, which could be main tracks, switches and crosses. They are usually short. In the Netherlands secondary tracks are named after the two elements they connect. An example of this is track w1-s20, which connects switch 1 to track 20. The model takes the length of all tracks in meters as input, as well as the useful length of main tracks. The useful length is defined as the physical length minus the parts that are not usable in normal operation. Parameters influencing the useful length are the minimum sight distance for signals, the presence of some sort of crossing infrastructure or the length of a platform or service facility, which could be lower than the track length. The physical length is used in the route determination step of the model, while the useful length is used in the capacity determination step. The model also requires the boundary elements of all tracks. Each track is connected to an infrastructure element on both ends. Boundary elements could be switches, crosses, other tracks or buffer stops. The boundary elements are used to determine potential routes in the route determination step of the model. Table 4 provides an overview of the location specific input data and its source.

For stabling yards in the Netherlands the data regarding the tracks is obtained from two sources. The first is the Infra-atlas. This is a tool created by ProRail to store data on all tracks in the Dutch rail network and it is most commonly used by organizations that require precise location data of the tracks, such as maintenance contractors. It includes data on secondary tracks, switches and crossings. This database does not contain data on the length of tracks, but for most tracks data regarding the (relative) location of a track is available. The dataset contains information on the local starting and ending point of a track on a corridor. This data is presented in kilometers with six decimal points, so it is accurate to the millimeter. The Infra-atlas dataset also contains the boundary elements for all tracks. It is however incomplete, as for some tracks one or two boundary elements are unknown. Furthermore, in some cases signals or stop signs are entered as boundary elements, which cannot always be used to determine the infrastructure element that is the actual boundary element.

For the main tracks data on the physical and useful length in meters of the track is available in the Single Source of Information (SSOI). The SSOI is a database of all stabling yards in the Netherlands. It is a joint database of NS and ProRail. Besides the useful length of tracks, the SSOI contains information about the functions of tracks, whether or not tracks can be assigned to NS for stabling purposes and whether or not tracks are electrified. Furthermore, the SSOI contains information on the current use of stabling yards by NS. This data is not used as input data in the model, but can be used to set the parameters for the model. Table 4 provides an overview of the location specific input data.

Data is also needed on the current use of the stabling yard. Information is needed about the time a train enters the stabling yard and the train composition. Furthermore, similar data is needed for trains leaving the yard. The sum of incoming train units should match the sum of outgoing units, so each unit can be assigned to a train service. This data is used to provide the model with general characteristics of the schedule. These are: train types present at the location, average and maximum amount of carriages per train and amount of trains arriving and departing per hour. This data is used to determine the duration of shunting movements, which have an effect on the shunting capacity. For each train unit the dataset has to contain the train type, amount of carriages, train series number, hour of arrival/departure and minute of arrival/departure.

For stabling yards in the Netherlands no accessible database is present that contains this information, but it can be provided per location on request by the Netwerk & Ontwikkeling department of NS. The standard schedule is provided for one night of the week. In this study the night from Monday to Tuesday is used. For other nights the schedule might be slightly different, but this aspect is not taken into account. It contains the arrival- or departure time accurate to the minute in a non-standard unit. It is stored as the hour of arrival multiplied by 100 plus the minute of arrival. An arrival time of 22:45 for example is presented in the database as 2245. This has to be separated into the hour of arrival and minute of arrival to be used in the model.

The arrival and departure times are used to indicate if the current shunting and buffer capacity is sufficient to handle the current schedule. The maximum capacity is determined assuming an optimal arrival and departure pattern of trains, which is not an accurate representation of normal operations. If the area around the yard includes a station and/or mainline tracks, data is also needed on all trains that use these tracks without the need to use the stabling yard. This is especially important if shunting movements require the use of tracks or switches also used by through going trains. The availability of shunting capacity is estimated by determining the amount of trains crossing the desired shunting route and the moments this happens. The data should contain the train series number, switch name and scheduled moment of passing as standard unit of time in seconds accurate. The train series number is needed in case the dataset contains duplicate entries that need to be ignored.

For stabling yards in the Netherlands data on the use of the infrastructure is obtained from the Inframonitor application. This ProRail tool allows you to visualize a schedule and analyze the occupation of switches through an integrated module. The dataset obtained from the Inframonitor contains duplicate entries that need to be removed. This is caused by the fact that the switch occupation module assesses switch occupation on a weekly basis for all trains present on the day the occupation is assessed. Train series that are scheduled 7 days a week are included 7 times. Trains that are not scheduled on the day of assessment are not included at all. In this study the occupation of switches has been determined for a standard Monday using the train schedule of 2018. The planned shunting movements have been excluded, as the goal is to determine the capacity for these kind of movements. Table 4 provides an overview of the location specific input data.

Table 4: Location specific input data

Data type	Source	Elements
Characteristics all tracks and switches	Infra-atlas (ProRail)	- Track/Switch name - Boundary elements - Local starting and ending point (km)
Characteristics main tracks	SSOI (ProRail, NS)	- Track name - Useful track length (m) - Track function(s)
Schedule stabling yard	Department Netwerk & Ontwikkeling (NS)	- Train number - Train type and composition - Time of arrival/departure
Switch occupation	Inframonitor (ProRail)	- Train series number - Switch name - Time of passing switch

4.3.2 General data and input variables

The general data mainly concerns the characteristics of the trains. Data is needed for all train types that are serviced on the location being assessed. In order for the model to be able to be used for all stabling yards in a country data is needed on all trains present in that country. The data has to contain the train type noted exactly the same as in the schedule for the current use of the stabling yard, the amount of carriages per train unit, the length of the train unit in meters and the time spend by the driver in each cabin when changing the direction of travel of a train in minutes. A differentiation is made between subtypes with a different length, so in the Netherlands for example the VIRM-4 and VIRM-6 are presented separately. This data is for example used to determine the average duration of a change of direction, the average occupation of a switch and whether or not a train fits on a certain track. For stabling yards in the Netherlands this data is obtained from the Single Source Of Information (SSOI) presented by ProRail and NS, the Netwerk & Ontwikkeling department of NS and (Janssens, 2017).

Several input variables are used in order to be able to change the service process. These variables allow an analysis of the stabling capacity of the yard when elements are adapted to better reflect the demand. An example is the function of tracks. Stabling yards that currently do not use a carousel process to service trains will likely have too much service capacity. The idea of 100% servicing is to centralize the different tasks, so a certain amount of tracks can be selected to use for servicing. The other tracks can be used for stabling or other tasks. Other input variables are the specific order of the process steps, the takt time and the percentage of trains that can be completely serviced within the takt time.

Table 5: General input data

Data type	Source	Elements
General train data	SSOI (ProRail); Department Netwerk & Ontwikkeling (NS); (Janssens, 2017)	- Train type - Amount of carriages per train unit - Train length (m) - Duration per cabin when changing direction (min)
General process characteristics	Department Netwerk & Ontwikkeling (NS); 100% servicing team Zwolle (NS); SSOI (ProRail)	- Takt time - Percentage of trains that is serviced within takt - Process order - Track function(s)

4.4 Model steps

This chapter describes the steps of the model and the way they are executed. The model consists of three main steps: data preparation, route determination and capacity calculation. In the first step all input data is processed and stored in a way it can be used for the other steps. In the second step the model finds all routes that a train might take between two tracks allocated to consecutive steps of the service process. For each combination of tracks the most favorable route is determined. In the last step the capacity is calculated for the different steps of the model, as well as the shunting capacity.

4.4.1 Data preparation

The first step of the model is data preparation. The amount of preparation the data requires depends on the quality of the input data. In cases where a stabling yard in the Netherlands is assessed, the track data from the SSOI and the Infra-atlas requires the most preparation. The data has to be combined into one dataset to be usable for the other steps of the model. The main adaptation that has to be done is the completion of the boundary elements on either side of a track. The SSOI does not contain this data. The Infra-atlas does contain data on the boundary elements. Boundary elements can be switches or other tracks, but can also be signals, stop signs, buffer stops or derails. Some boundary elements are not entered in the database and others are inconsistent. The main problem occurs with tracks that have a signal or stop sign as boundary element. These tracks usually connect to a switch or short track section leading to a switch, but the boundary element of these tracks is usually not the signal or stop sign. Boundary elements of switches are not entered into the database at all. Several adaptations are needed to determine the connection of a track. It can be deduced from the name of some short track sections, which are usually named after the tracks and/or switches they connect. An example would be track w1-s2, which would connect switch 1 to track 2. For tracks where this technique is not an option, the local measurement data is used. The start- and end point of tracks on a local scale is included in the data in kilometers with six decimals and should be exactly equal for two connecting tracks and/or switches. In most cases this number is unique, so connections can be determined. In the cases the number is not unique, the data has to be manually added.

Connections with crossing switches cannot be automatically determined from the data, as they are directly connected to switches that lack the connection data. Per crossing switch four track sections with a length of zero meters have to be added manually to add these connections. The same is true for two switches that are directly connected to another switch, although these seem to be rare. In Eindhoven for example one such direct switch to switch connection exists.

For the route determination it is important that the boundary elements of all tracks are consistent with the direction. Each track has a ‘beginning’ and an ‘ending’ boundary element. In order to prevent the route determination algorithm from choosing paths that contain impossible turns at switches, the beginning and ending boundary element of all tracks needs to be in the same direction. In the raw data this is not always the case. Tracks that have their boundary elements the other way around need to have these elements manually swapped in order for the route determination algorithm to work properly. It does not matter which direction is chosen, as long as all tracks have the beginning boundary element on the same side. This has to be done manually.

The data regarding the current use of the stabling yards in the Netherlands obtained from NS Netwerk & Ontwikkeling only has to be altered slightly. The data contains information on characteristics of arriving and departing train units instead of trains. Trains can consist of more than one train unit. Train units that are the same type and have the same train number and arrival time are combined into one train. The amount of carriages and total length of the train is calculated by taking the sum of the amount of carriages and length of each train unit. The time a train leaves active service or enters active service is presented in the dataset without any punctuation marks, so this has to be changed. For example a train leaving active service at 21:45 is represented as 2145. Furthermore, the dataset might contain entries of trains that are serviced at the location, but parked somewhere else. These are mentioned separately, but have to be included in the main dataset. The total length of these trains can be added to the additional stabling capacity in the capacity calculation in order to properly account for this.

The switch occupation data also has to be prepared to be used. For Dutch stabling yards, the Inframonitor tool used to obtain the data determines switch occupation for an entire week for all train series active on the day of examination, while only data about occupation on this specific day is needed. Therefore duplicates have to be removed. The data also represents an English switch as two separate switches. The data of the two separate switches have to be combined in order to represent the passing of an English switch, as the track data from the Infra-Atlas only contains the combined English switches. As the scheduled moment of passing of the two switches of an English switch are the same, duplicate switch passings have to be removed from the dataset.

4.4.2 Route determination

Specific routes for trains have to be determined for shunting movements between different steps of the process. These routes are required in order to determine the use of certain infrastructure elements. The steps of the service process are assumed to always be followed in the correct order and are performed at certain assigned tracks, so the number of routes between tracks assigned for two consecutive steps is limited. Figure 8 provides an overview of the process steps and the routes that have to be planned. All steps of the stabling process take place at a separate track on the stabling yard, so all arrows represent movements of trains, except for the arrow from service main to the decision if the service is completed. Leaving active service is the moment the last passengers disembark from the train and the train can enter the stabling process. Entering active service is the moment the first passengers enter the train. All trains go through all steps in figure 8, with the exception of additional service. This step is only used by trains that cannot be fully serviced within the takt time.

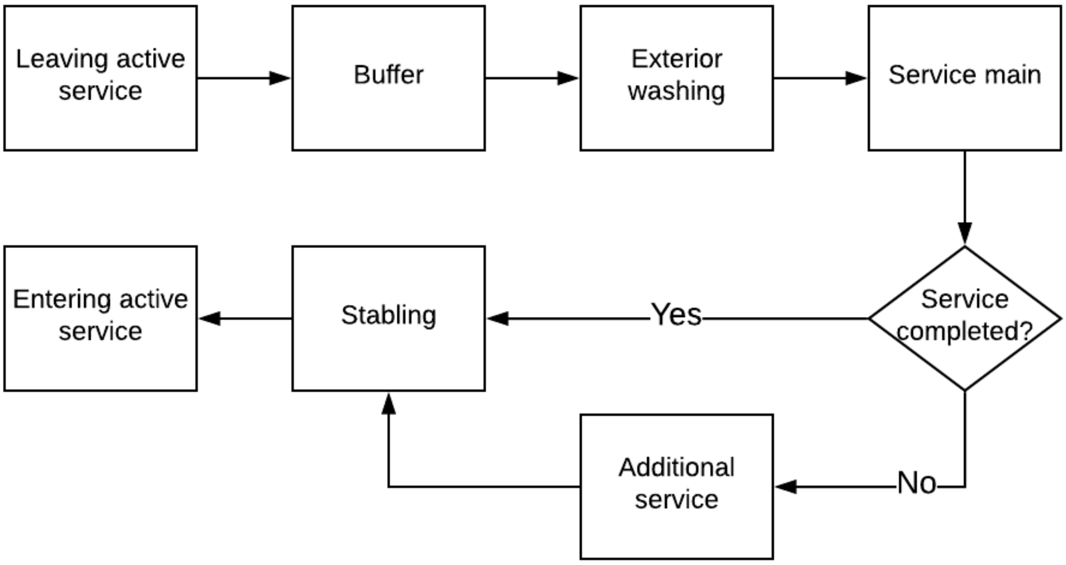

Figure 8: Schematic overview of process steps

Several tracks may be assigned to one step of the service process. Especially for stabling there are often multiple tracks available. In total there are seven combinations of steps that require routes to be planned between the assigned tracks. Table 6 shows these combinations. Routes are planned between all pairs of tracks of two steps, so if for example there are four platform tracks and two buffer tracks, 4 * 2 = 8 Routes are planned. This leads to a set of routes for all movements between two consecutive steps of the process. The route determination step of the model leads to seven sets of routes, one for each of the seven combinations in table 4. In general all trains have to follow one of the determined routes from the set of routes. However, not all trains are required to go to the additional service track(s), as this step is only for trains that fail to be fully serviced in the set takt time. Most trains will go from main service directly to stabling, while some will go to service extra in between. For the route determination step of the model this does not have any influence, since routes are still required. It is assumed that all trains serviced at a location also start their active service there, so in the first set of routes all trains come from a platform track and in the last set of routes all trains go to a platform track. In reality some trains might drive empty to another station, but this is not taken into account in this model.

Table 6: Combinations of process steps that require train movements

From:	To:
Platform (leaving active service)	Buffer
Buffer	Washing machine
Washing machine	Service main
Service main	Service extra
Service main	Stabling
Service extra	Stabling
Stabling	Platform (entering active service)

An algorithm is used to determine the possible routes between two tracks that require a route. Figure 9 shows the steps of the algorithm. It starts by finding the two boundary elements of the start track in the database of all tracks. If a boundary element is not a buffer stop or another track, the algorithm then searches the database for all tracks that have the same boundary element, but on the opposing side. So if the starting track has for example ‘switch 1’ as a beginning boundary element, it searches for tracks that have ‘switch 1’ as ending boundary element. This way the model can find one or two connecting tracks per boundary element, depending on the direction of the switch. The tracks that are found this way are added to the list of tracks to be examined in the next step of the algorithm. If the boundary element is another track, the algorithm does not search for tracks with the same boundary element, but directly sets this new track as (one of) the new tracks to be examined. If the boundary element is a buffer stop, the algorithm does nothing as the track is a dead-end.

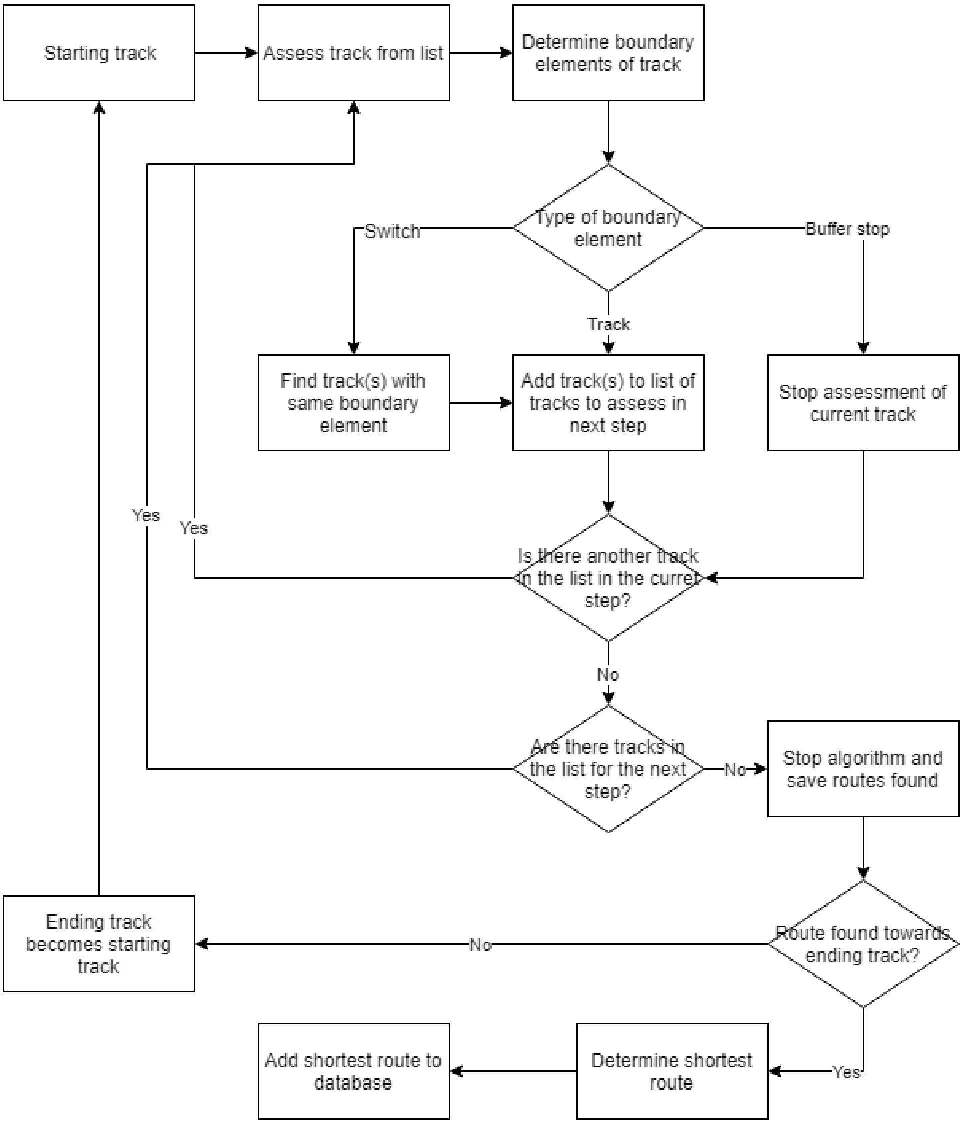

Figure 9: Flow diagram of algorithm used

The next step of the algorithm is to repeat the process described above for all tracks found to be directly connected to the previously examined track. A provision is added to the algorithm that prevents adding tracks to the list that require changing direction. This automatically also prevents the previous track on the specific route to be added again. The algorithm continues these steps until it cannot expand any of the routes anymore, either because buffer stops or the edge of the assessment area are reached. A limit of 100 steps has also been built into the model to potentially reduce the computation times. This limit is large enough to find at least some of the routes on the largest stabling yards.

In the next step the model determines if routes have been found that connect the starting track to the destination track. If this is the case, all routes found that provide this connection are added to the database of routes, including all tracks that are passed on the route. If no direct routes are found, the algorithm is used again, but this time with the target ending track as the starting point. The model then determines if there are tracks that can be reached from both the starting and ending track. This means a route is possible with one change of direction. If one or more of these tracks are found and these tracks are in the database of tracks where changing direction in the middle of a shunting movement is allowed, the algorithm is used again for combinations of starting track with track to change direction and with track to change direction with ending track. All combinations of routes that are found are added to the database of routes. If no routes are found with one change of direction, the model designates the combination of the starting and ending track as infeasible. A route with more than one change of direction might be possible, but this is very undesirable as it takes up a lot of shunting capacity and train driver resources. The model therefore ignores this option.

The next step is to determine the preferred route for each combination of starting and ending track. For each route found the total length is estimated. Exact data on the length of tracks is only available for the main tracks that are presented in the SSOI data. For the short connecting tracks and switches this data is not fully present. The short tracks that are added manually do not have a known length. Therefore the average length of these tracks that are in the database is determined. This value is used for all short tracks. This leads to inaccuracy in the calculated route length, but the relatively small length of these short tracks compared to the main tracks limits the effect of this inaccuracy. Switches also have a length, but this is not included in the data at all. The length of a track section of a switch depends on the radius of the converging track of the switch. On stabling yards and around stations the speed of trains is often low, so mainly switches with a small radius (1:9 angular ratio) are used. Switches with this angular ratio usually have a length of the track sections of 27 meters (Dura Vermeer, unk.). This value is used for all switches. English switches and switches with a larger radius have longer track sections, so using this value leads to an underestimation. However, switches with a radius larger than 1:9 are very uncommon on stabling yards due to costs and the difference with English switches is only a couple of meters, so the effect is limited. The exact amount of switches in a route is not known, as only the tracks are saved in the route database. The total amount of switches and tracks at a location is however known, so a ratio of switches to tracks can be determined. This is done for each location specifically. It is likely that this method leads to an underestimation of the amount of switches on most routes, as tracks on stabling yards are less likely to have small tracks connecting main tracks to a switch compared to station- and mainline tracks. The effects of this underestimation are limited, as the route length is only used to determine the shortest route and routes between two specific tracks often partly overlap and use similar types of tracks.

For each set of starting and ending tracks the estimated length of all routes are calculated with formula (4.1). From all route options between two specific tracks the model determines the route with the shortest length. This route is used in the remainder of the model for all movements between these two tracks. In more elaborate shunting models generally the cost of a route is determined. There are however few parameters linked to cost other than length, so this study uses the shortest route. It is also used in order to minimize the duration of shunt movements and the infrastructure occupation, which both positively influence the capacity. As this model aims to provide a simple estimation, no route optimization is used. Other train movements are therefore not taken into account when determining the best route. This potentially leads to many routes using the same infrastructure, while alternatives are available. This limits shunting capacity, but does allow for a simple model.

$$L_{route} = \sum_{i \in S_{main}} (L_{track_{main},route}) + N_{track_{secondary},route} * L_{short} + f * N_{track_{total},route} * L_{switch} \quad (4.1)$$

L_{route} [m]	Total length of a route
$L_{track_{main},route} \in S$ [m]	Length of a main track in route
S_{main}	Set of main tracks in route

$N_{track_{secondairy},route}$	Amount of short tracks in route
L_{short} [m]	Average length of a short track
f	Switch to track ratio
$N_{track_{total},route}$	Total amount of tracks in route
L_{switch} [m]	Average length of switch element

The next step of the model is to determine the relative demand for a certain track per set of routes. If for example 4 out of 8 routes from the set require the use of track 1, the relative demand for this track is 50%. This is done because the model assumes an equal division of demand over the routes between two steps of the model. In reality trains would drive to the most logical track in the next step (if available), so the accuracy of the model might be limited if a process step has many tracks assigned to it. If the 4 routes used as an example earlier require a direction change that forces a track to be used twice per route, the relative demand would be 100%. The maximum relative demand is therefore 200%. This dataset is then used in the capacity determination.

4.4.3 Capacity determination

The capacity of the service process with 100% servicing depends on the capacity of each element of the process individually. The capacity is calculated in meters. In some cases the maximum hourly throughput is calculated first. This is later converted to capacity. The following elements are part of the total stabling capacity:

- Physical stabling capacity
- Main service capacity
- Additional service capacity
- Exterior washing capacity
- Shunting capacity
- Buffer capacity

Physical stabling capacity

The physical stabling capacity and the main service capacity are the most straightforward to calculate. The physical stabling capacity can be calculated by taking the sum of the useful length of all tracks dedicated for parking trains and correcting it for operational losses by using a so-called cutting loss. ProRail and NS maintain a cutting loss of 7%. This means 7% of the track length is not included in the capacity calculation. Therefore a cutting loss factor of 0.07 is used to reduce the maximum length of a track. Additional stabling capacity such as stabling on platform tracks or at other (nearby) locations is not included in this number. These values are not calculated, but obtained from the SSOI and stabling yard schedule data. Because the presence of additional capacity and the use of platform tracks can differ significantly per location, these have to be added separately to the total physical stabling capacity. Formula (4.2) and (4.3) show the calculation for the physical stabling capacity and total stabling capacity in meters. This unit of measurement for the capacity is currently becoming more common in the Netherlands. To obtain a capacity in amount of carriages the value has to be divided by the standard carriage length used by ProRail and NS, which is 27.2 meters. This is the length of the longest carriage in the fleet, so using this value causes an underestimation of the actual capacity. The scale on which this happens depends on the types of trains that use the location, as carriage length can differ significantly between train types. The capacity in carriages is always rounded down to full carriages. The model first calculates all capacities in meters and converts all to carriages in the final capacity calculation.

$$C_{stabling} = \sum_{i \in S_{st}} (L_{stabling,i}) * (1 - c_{loss}) \tag{4.2}$$

$$C_{stabling_{total}} = C_{stabling} + C_{stabling_{platform}} + C_{stabling_{extra}} \tag{4.3}$$

$C_{stabling}$ [m]	Physical stabling capacity
$L_{stabling,i} \in S$ [m]	Length of a stabling track i
S_{st}	Set of stabling tracks
$c_{loss} = 0.07$	Cutting loss factor
$C_{stabling_{total}}$ [m]	Total physical stabling capacity
$C_{stabling_{platform}}$ [m]	Stabling capacity at platform tracks
$C_{stabling_{extra}}$ [m]	Stabling capacity at different locations

Main service capacity

The main service capacity depends on two variables: the sum of the length of the service tracks and the takt time. This can be done because trains that exceed their takt time are moved to a separate track and the assumption is made that NS will provide enough personnel to allow the desired takt time to be achieved. In this study a takt time of 90 minutes or 1.5 hours is used. Having a lower takt time would increase capacity, as trains spend less time at a service track. This would however require more personnel to service trains in order to make the takt time, which would increase cost for NS. Furthermore, even with sufficient personnel it is likely the percentage of trains that can be fully serviced within the takt time decreases, as the duration of certain tasks could approach the takt time. There would be less time left to recover from something going wrong, such as a piece of equipment not working properly.

Since the length of trains does not always equal the length of the tracks, the same 7% cutting loss has to be taken into account. Formula (4.4) shows the calculation of the maximum hourly throughput in meters per hour. At a later step in the model this is converted into the main service capacity in meters. In reality the capacity calculated this way might not be achievable, as it is possible the length of the service tracks might not be fully usable all the time. The model assumes more than one train can be serviced at the same track at the same time, which would on average fill the tracks up all the way (taking the cutting loss into account). However, as the order in which trains go through the process is sort of fixed, this might not always be the case. The main service capacity calculated in the model is therefore a maximum capacity, that can only be reached if the arrival pattern of trains is suitable.

$$H_{service_{main}} = \frac{\sum_{i \in S_{sm}} (L_{service_{main},i}) * (1 - c_{loss})}{t_{takt}} \tag{4.4}$$

$H_{service_{main}}$ [m/h]	Maximum hourly throughput of main service
$L_{service_{main},i} \in S$ [m]	Length of a main service track i
S_{sm}	Set of main service tracks
t_{takt} [h]	takt time

Additional service capacity

Calculating the additional service capacity is more complicated. It depends on the amount and length of the additional service track(s), the average time trains require for additional servicing and the percentage of trains that requires additional servicing. The average time set for additional servicing is estimated to be 0.75 hours (45 minutes) by the NS-team testing the concept in Zwolle. This value is used in this study. The average percentage of trains that require additional servicing with the use of a takt time of 90 minutes is estimated by NS to be 8%. Therefore a value of 0.08 is used in this study for the factor that takes this into account. If the takt time is altered, this value might also change. The model provides an overview of the maximum capacity of this step, so it assumes trains arrive evenly distributed. In reality this is not the case. It is possible that a train requires additional servicing while the additional servicing track(s) are occupied. This would disturb the process and should be prevented as much as possible. The model therefore calculates and presents the margin for the additional servicing capacity by dividing the additional service capacity by the lowest calculated capacity of the other elements. It can later be decided if this value is acceptable and if therefore this step would provide the lowest capacity of all elements. Formula (4.5) shows the calculation of the maximum hourly throughput of the additional service track(s).

$$C_{service_{extra}} = \frac{\sum_{i \in S_{se}} (L_{service_{extra},i}) * (1 - c_{loss})}{t_{service_{extra}} * c_{service_{extra}}} \tag{4.5}$$

$H_{service_{extra}}$ [m/h]	Maximum hourly throughput of additional service
$L_{service_{extra},i} \in S$ [m]	Length of additional service track i
S_{se}	Set of additional servicing tracks
$t_{service_{extra}} = 0.75$ [h]	Average time it takes to perform additional servicing
$c_{service_{extra}} = 0.08$	Factor for percentage of trains that require additional servicing

Exterior washing capacity

The exterior washing capacity depends on the amount of washing machines, the speed at which trains drive through them, the average time it takes to wash a cabin and whether or not a direction change is needed after washing (for example when the TWI is on a dead-end track). The duration of the headwash of a train of NS takes 7 to 10 minutes, depending on the type of train. In this study the average value is used, so the duration is set at 8.5/60 hours (8.5 minutes). All trains have a cabin on either side, so two heads need to be washed per train. In order to calculate the duration of the part of the washing where the sides are washed the speed of the washing machine is used. Most TWI's in the Netherlands manage an average side washing capacity of 60 standard carriages per hour (1 carriage per minute). This value is used in this study. On stabling yards that service several types of trains these are likely accurate assumptions, but on locations where only one or two types of trains are serviced this might lead to an over- or underestimation of the exterior washing time of potentially several minutes. It is worth noting that larger locations generally service more types of trains and 100% servicing is not being considered for the smallest locations in the Netherlands. Formula (4.6) shows the average time it takes to wash a train. A factor c_1 is used to indicate if a direction change is needed after washing. The direction change can be initiated when the second head is being washed, so additional time for the direction change is only added if this takes longer than the washing of the second head. The factor is 1 if a direction change is needed and this takes longer than the washing of the second head and 0 otherwise.

$$t_{TWI} = 2 * t_{headwash} + \frac{L_{train_{avg}} \big/ L_{bak}}{c_{TWI}} + c_1 * (t_{change_{direction}} - t_{headwash}) \tag{4.6}$$

t_{TWI} [h]	Average duration of exterior washing of a train
$t_{headwash} = \frac{8.5}{60}$ [h]	Average time it takes to wash the head of a train
$L_{train_{avg}}$ [m]	Average length of trains using the TWI
$L_{bak} = 27.2$ [m]	Standard length of a carriage
$c_{TWI} = 60$ [carriages/h]	Washing capacity of sides of carriages of the washing machine
$c_1 = \begin{cases} 0 \\ 1 \end{cases}$	Factor for direction change: 1 if direction change, 0 otherwise
$t_{change_{direction}}$ [h]	Average time it takes to change the direction of a train

The direction change of a train mainly depends on resetting the onboard systems and the walking time for the driver. Therefore changing direction can be done while the last head is being washed. The time it takes to change direction depends on the time the driver has to spend in each cabin and the walking speed. The average time the driver has to spend in each cabin is 1/12 hours (5 minutes), according to NedTrain standards. In one cabin the systems have to be shut down, while in the other they have to be restarted. Therefore this value has to be included twice in the calculation. The average walking speed used as standard by NedTrain is 4000 m/h (4 km/h). Formula (4.7) shows the average time it takes to change the direction of driving of a train. The maximum hourly throughput of exterior washing can then be determined with formula (4.8). The amount of tracks equipped with a washing machine is multiplied by the hourly throughput in trains per hour per washing machine (one divided by the average duration of exterior washing of a train) multiplied by the average length of a train to define the maximum hourly throughput in meters per hour.

$$t_{change_{direction}} = 2 * t_{cabin} + \frac{L_{train_{avg}}}{v_{walk}} \tag{4.7}$$

$$H_{twi} = N_{tracks_{TWI}} * \frac{1}{t_{TWI}} * L_{train_{avg}} \tag{4.8}$$

$t_{cabin} = \frac{1}{12}$ [h]	Average time driver spends in each cabin for change of direction
$v_{walk} = 4000$ [m/h]	Average walking speed of train driver
H_{twi} [m/h]	Maximum hourly throughput of the washing machine(s)
$N_{tracks_{TWI}}$	Amount of tracks equipped with a TWI
t_{TWI} [h]	Average duration of exterior washing of a train

Shunting capacity

The shunting capacity is the most difficult to determine. It combines the data from all the routes found in the capacity determination with the switch occupation data from Inframontitor. The data from Inframonitor is arranged into the amount of passages of trains per switch per hour, for the 24 hours in a standard Monday. For all routes determined in the previous step of the model, the demand per track (including the small connecting tracks) is given per set of routes (for example all routes from the buffer to the TWI) as percentage of routes from the set of routes that requires the use of this specific track. The assumption is made that all routes in a set of routes are used equally. This could potentially lead to illogical routes being used. A simple example of this can be found in figure 8. The model assumes trains that have been serviced at track 1 are evenly distributed over stabling tracks 3 and 4, but it makes more sense to route all trains from service track 1 to stabling track 3 and from track 2 to track 4. In this example the effect is limited to an increased use of the cross in the middle, but on a large location tracks assigned to the same step of the process could be located much farther apart. This could lead to a higher demand for shunting capacity on certain infrastructure elements than necessary, which could lead to a lower overall shunting capacity. If tracks are assigned to certain steps of the process in a way that these tracks are bundled together, the impact of this assumption is limited, as it is likely that the routes use much of the same infrastructure. If this is not the case the effect could be significant, so the accuracy of the shunting capacity is low.

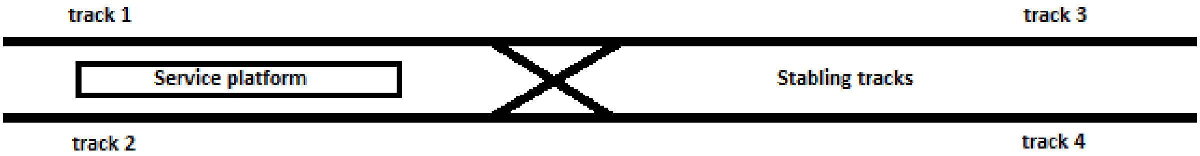

Figure 10: Example track layout where model could assume illogical routes

The demand per track per set of routes has to be transformed into demand per switch instead of per track, as this corresponds to the switch occupation data. To do this the switches that connect to each track are obtained from the database. Per set of routes the percentage of routes from the set that use the track are copied to the connecting switch(es). A distinction is made between tracks that have the specific switch as their beginning or ending boundary element. If there are two tracks per set of routes that have the switch as their beginning or ending boundary element, the percentages are added up. At the end all percentages for beginning and ending boundaries per switch should be the same and can be copied to the final database. A check is built in to verify this. There are three sets of routes that not all trains have to use. The routes to and from the extra service track(s) is only used by the trains that fail to be serviced in the set takt time. Likewise, the routes from the servicing tracks to the stabling tracks are only used otherwise. The percentages of per switch of these sets of routes are reduced by multiplying it with the percentage of trains that requires this set of routes.

The next step is to determine the maximum shunting capacity that is left on each set of routes. The remaining capacity differs per hour, as the amount of trains that pass certain switches also differs per hour. For each set of routes the algorithm looks at each switch in the set and adds the exact time a train passes the switch to a database. This is done for every hour in the day separately. These times represent the moment one of the switches needed for at least one route from the set of routes is occupied, and a shunting movement can therefore not take place. Movements over switches are planned with a norm time of 0,05 hours (180 seconds). This means the maximum amount of trains a switch can handle per hour is 20, but only if they arrive exactly 180 seconds after each other. Because one train can use several switches in the set of routes and two trains could pass two separate switches on the route at (nearly) the same time, there is overlap present in the database of times that the planned route is not clear. Therefore, the exact times are used to determine how many seconds per hour at least one of the routes from the set is blocked. This can be calculated back to the effective amount of trains per hour by dividing by 180 seconds. The maximum hourly throughput on the set of routes is then the maximum capacity (20 trains) subtracted by the effective amount of trains already planned. Formula (4.9) shows this calculation.

$$H_{unused,set} = H_{shunt\_max} - \frac{1 - \sum_{i \in S_t}(t_{occupied,set,i})}{t_{plan}} \tag{4.9}$$

$H_{unused,set}$ [trains/h]	Maximum hourly throughput of all switches in a set of routes not occupied by other trains
$H_{shunt\_max} = 20$ [trains/h]	Maximum hourly throughput of all switches in a set of routes
$t_{occupied,set,i}$ [h]	Time any switch on a set of routes is occupied without overlap

S_t Set of times a switch is occupied in the hour assessed
$t_{plan} = 0.05$ [h] Standard planning time for a shunting movement (180 seconds)

The next step is to determine per set of routes per hour how many shunting movements can take place. The database contains per switch per set of routes which percentage of possible routes requires the use of this switch. For each of the seven sets of routes the most critical switch can be determined. This is the switch that has the largest percentage of routes from that set using it. It could be as high as 200% if all routes from the set require a change of direction and therefore the switch is passed twice per route. As the 100% servicing concept is set up as an assembly line, all trains go through all sets of routes, with the exception of the sets of routes involving additional servicing. Therefore the sum of the percentages for each set of routes is determined for these most critical switches. This is the total percentage of routes that require the use of this switch. It could be as high as 1016% if all routes from the 7 sets require to use it twice. This is however extremely unlikely to happen.

The maximum hourly throughput for shunting per set of routes per hour is determined by dividing the remaining hourly throughput per set of routes per hour by the usage percentage of the most critical switch of this set of routes. This can be seen in formula (4.10). The remaining hourly throughput has been calculated in formula (4.9) in trains per hour. If for example for a total of 1800 seconds in a certain hour none of the switches used on any route from the washing machine to the service tracks is used, the remaining capacity is 10 trains. If the usage percentage of the most critical switch is 400%, the shunting capacity for this set of routes for this hour is 2.5 trains. A 400% usage percentage could for example occur if one switch is needed for all routes within three sets of routes, and in one set of routes it has to be used twice due to a change of direction. This calculation is only accurate if all trains arrive at the exact moment a switch is free, so it is the maximum shunting capacity. However, the method to determine the remaining capacity does not take into account that gaps in which the routes are clear might be smaller than the standard planning time of shunting movements of 3 minutes. If a shunting movement were to use a gap that is too small, the next train would have to wait. This is usually not acceptable when creating a schedule, so the shunting capacity is likely overestimated. In reality, however, the standard time of 3 minutes allows for some margin for delayed trains, so the scale of the overestimation of the capacity depends on the willingness to use some or all of this margin. The accuracy of the shunting capacity is further reduced by the fact that only the moment all switches in a set of routes are clear is assessed, instead of switches on a specific route. It is therefore possible that on one of the routes in the set of routes all switches are clear and a movement is possible, but the model assumes this is impossible because a switch on another route in the set of routes is occupied. This leads to an underestimation of the actual capacity.

$$H_{shunting_{hour\_set}} = \frac{H_{unused\_hour\_set}}{f_{shunt_{total\_set}}} * L_{train\_avg} \tag{4.10}$$

$H_{shunting_{hour\_set}}$ [m/h] Maximum hourly throughput per hour per set of routes
$f_{shunt_{total\_set}} \in [0,1]$ Usage probability of most critical switch in set of routes

The maximum hourly throughput for shunting for the entire service process can be determined by taking the lowest value of the throughput for shunting of the seven sets of routes for that hour. This way the most critical switch for the entire service process is found and used to determine the total capacity. This is possible because the amount of train movements between steps of the process is equal, as all trains go through it the same way. If one train enters the process, it has to go through all steps in order. The reduced amount of shunting movements for the additional servicing tracks has been taken into account in the calculation of the total demand percentages per switch. Formula (4.11) below shows the calculation of the shunting throughput per hour.

$$H_{shunting\_hour} = \min_{i \in S_{sh}} \left(H_{shunting_{hour_{set}},i}\right) \tag{4.11}$$

$H_{shunting_{hour}}$ [m/h]	Maximum hourly shunting throughput per hour per set of routes
S_{sh}	Set of shunting capacities per hour per set of routes

Shunting capacity also includes tracks where trains change direction as potential bottlenecks. Each track has a maximum amount of trains that can change direction in an hour. This throughput is determined by dividing 1 hour by the average time it takes to change direction. The average time for a direction change is calculated with formula (4.7). This does however not include the time a track is occupied by the train before the next train can enter the track. Therefore the standard norm time of 0.05 hours (3 minutes) is added to a direction change. The maximum throughput for a track where trains change direction is calculated in meters per hour with formula (4.12).

$$H_{change\_max} = \frac{1}{t_{change_{direction}} + T} * L_{train\_avg} \tag{4.12}$$

H_{change_max} [m/h]	Maximum throughput to change direction on a track per hour
$t_{change_{direction}}$ [h]	Average time it takes to change the direction of a train
$T = 0.05$ [h]	Standard track occupation during a shunting movement

This formula does not take relative demand into account. For each track where a change of direction is allowed the percentage of routes from the total amount of routes that use this track is determined. The actual shunting capacity related to direction changes for each track is determined by dividing the maximum capacity by this percentage. This provides the maximum shunting throughput per hour for the entire service process that does not require more direction changes per hour than possible. Formula (4.13) shows the calculation of the final shunting throughput per track where a direction change is allowed.

$$H_{change_{final}} = \frac{H_{change\_max}}{f_{change}} \tag{4.13}$$

$H_{change_{final}}$	Final hourly shunting throughput per track with changing direction
f_{change}	Ratio of routes that requires a direction change on a track

The final shunting throughput per hour is the lowest value of the shunting throughput calculated with formula (4.11) and the lowest shunting throughput for direction changes calculated with formula (4.13). The model provides an overview of the shunting capacities per hour, as well as the minimum, maximum and average shunting capacity per hour. The average value is used in the overview of all capacities.

Buffer capacity

The buffer capacity is also difficult to determine. In reality it needs to make sure that if more trains enter the process than the process can handle, trains can wait here until they can enter. Furthermore, some train units will need to wait in the buffer for another train unit to combine into one train. Since this model attempts to estimate the service capacity, the exact arrival pattern and train composition plan is unknown. A general rule of thumb is that 80% of trains leave active service in the correct composition. This value is used in the buffer capacity calculation. The hourly throughput of the buffer can be calculated with formula (4.14).

$$H_{buffer} = \sum_{i \in S_{buf}} (L_{buffer,i}) * (1 - c_{loss}) * t_{buffer_{avg}} \tag{4.14}$$

H_{buffer} [m/h]	Hourly throughput of the buffer
L_{buffer} [m]	Length of buffer track i
S_{buf}	Set of lengths of buffer tracks
$t_{buffer_{avg}}$ [h]	Average time a train spends in the buffer

However, the average time a train spends in the buffer is unknown. The minimum time a train has to spend in the buffer can be determined. It is the 180 seconds norm time for the track occupation if a train can leave the buffer immediately after arrival. If a direction change is needed inside the buffer, the average time this takes times the percentage of buffer tracks that require a direction change has to be added. Formula (4.15) shows this calculation.

$$t_{buffer\_min} = T + f_{change_{buffer}} * t_{change_{avg}} \tag{4.15}$$

t_{buffer_min} [h]	Average minimum time a train spends in the buffer
$T = 0.05$ [h]	Standard track occupation during a shunting movement
f_{change_buffer}	Ratio of trains that require a change of direction in the buffer

This minimum buffer time does not take into account the unevenly distributed arrival pattern of trains and the necessity for waiting on another train unit to combine with. The average time these two steps take are however unknown, since the amount of trains is unknown. The buffer capacity is therefore not calculated on its own. Several combinations of standard values are used to calculate the buffer capacity if these values are (close to) the real values. The model will then determine with which values the buffer capacity would be sufficient on average. Formula (4.16) shows the calculation of the average buffer time and the standard values that will be used to calculate the buffer capacity.

$$t_{buffer_{avg}} = t_{buffer\_min} + t_{wait_{avg}} + f_{composition} * t_{composition_{avg}} \tag{4.16}$$

t_{buffer_avg} [h]	Average time a train spends in the buffer
$t_{wait\_avg} \in \{0, 0.167, 0.333, 0.5, 0.667\}$ [h]	Average time a train has to wait in the buffer
$f_{composition}$	Ratio of trains that need recomposing
$t_{composition\_avg} \in \{0, 0.25, 0.5, 0.75, 1\}$ [h]	Average time a train has to wait for recomposing

The percentage of trains that arrive per hour is also presented in order to evaluate if the arrival pattern could cause capacity problems at certain hours.

Total stabling capacity

To be able to determine the capacity of the total service process the throughputs of the elements determined in this chapter all have to have the same unit of measure. All throughputs are calculated in meters per hour, the physical stabling capacity in meters. Therefore the throughput values have to be converted into total amount of meters and carriages per shift. To do this the hours of operation are needed.

From the data regarding the current use of the stabling yard the moment the first train leaves active service (and thus enters the service process) and the moment the last train enters active service can be determined. The amount of hours the stabling yard is effectively in operation is calculated by taking the timespan between these two moments and subtracting it with the estimated time trains spend in the service process. The last train has to start the service process at least this amount of time before the moment it starts active service in order to be ready in time. This value is calculated by taking the sum of the known times for different elements of the service process and adding time for the shunting movements. The time for additional servicing is included, because the last train might require this and still needs to be on time. An average time for shunting movements is only included for 6 movements instead of 7, as the last train can go directly from the additional service track to the platform instead of being parked first. The average process time is calculated with formula (4.17).

$$t_{process_{avg}} = t_{takt} + t_{service_{extra}} + t_{TWI} + t_{buffer_{avg}} + 6 * t_{shunt_{avg}} \tag{4.17}$$

$t_{process_{avg}}$ [h]	Average time it takes a train to complete the process
$t_{shunt_{avg}}$ [h]	Average duration of a shunting movement

The average shunting time is calculated by taking the average length of all routes determined in the route determination step and dividing it by 15 km/h. This is the standard speed limit on stabling yards. It is assumed that trains accomplish this speed for the entire route. In reality acceleration and braking might take some time, so this assumption leads to some inaccuracy. This is however only a small part of a shunting movement. The shunting speed is entered in meters per hour in order to keep the consistency in the units. The average time it takes to change direction is added by multiplying it with the percentage of routes that require a change of direction. The average shunt time is calculated with formula (4.18). This value is then substituted into formula (4.17).

$$t_{shunt_{avg}} = \frac{\sum_{i \in S_{routes}} L_{route}}{N_{routes}} * \frac{1}{v_{shunt}} + t_{change_{avg}} * \frac{N_{change}}{N_{routes}} \tag{4.18}$$

L_{route} [m]	Length of a route
S_{routes}	Set of routes used for shunting
N_{routes}	Total amount of routes
v_{shunt} [m/h]	Average shunting speed
N_{change}	Amount of routes that require a change of direction

For the full overview the model also provides the amount of hours the service process can be in action before the physical stabling capacity is fully used. For all elements of the capacity that are presented as a throughput per hour, the total capacity per night shift is calculated with formula (4.19). In this formula the total main service capacity is used as an example, but the formula is used in a similar way for the buffer-, exterior washing, additional service and shunting capacity.

$$C_{service\_main\_total} = H_{service\_main} * t_{process_{avg}} \tag{4.19}$$

$C_{service\_main\_total}$ [m]	Total main service capacity in a night shift
$H_{service\_main}$ [m/h]	Maximum throughput for main servicing per hour

The total stabling capacity is determined by taking the lowest value of the calculated capacities of the different elements of the service process. All previously described elements of the capacity are included, except the buffer capacity. This is done because the buffer capacity is not estimated in this study, but only calculated for certain assumed values and presented separately. Formula (4.20) shows the calculation of the total capacity. As the process is set up as an assembly line, the element with the lowest capacity represents the bottleneck on the assembly line. Other stations might be able to handle a higher capacity, but this will just cause a waiting line for the station that is the bottleneck.

$$C_{total} = \min([C_{stabling}, C_{service\_main\_total}, C_{service\_extra\_total}, C_{TWI\_total}, C_{shunting\_total}]) \quad (4.20)$$

C_{total} [m]	Total capacity of stabling yard
$C_{stabling}$ [m]	Total physical stabling capacity
$C_{service\_main\_total}$ [m]	Total main service capacity
$C_{service\_extra\_total}$ [m]	Total additional service capacity
C_{TWI_total} [m]	Total exterior washing capacity
$C_{shunting\ total}$ [m]	Total shunting capacity

4.5 Model validity

Validation of the model is important. It provides an insight in the level at which the model represents reality. This way it can be determined for which purposes the model could be used. The main output of the model is the estimation of the maximum capacity of the different elements of the service process at the examined location. This way the general effect of changes to the infrastructure layout or the service process can be estimated quickly. When using the model to draw conclusions the limitations need to be considered. In this chapter the validity of the model is done per element of the total capacity of a stabling yard. The calculation of the maximum operating time is treated first, as this element is used in the calculation of all capacities except the physical stabling capacity. The model is validated using the initial run from the case study of the stabling yard in Eindhoven. Details about this location and the parameters for this initial run can be found in Chapter 5.1. As the buffer capacity is not estimated but a range of parameters is given that would cause the buffer to not be the bottleneck of the process, it is not validated.

4.5.1 Maximum operating time

Most of the elements of the capacity of a stabling yard are calculated in meters per hour and later converted to carriages per hour. The stabling capacity is however calculated in meters and carriages, as this element of the total capacity does not depend on time. In order to compare the elements of the total capacity and determine which element is the bottleneck, all elements must have the same unit. The model uses a maximum operating time for a stabling yard in order to do this. This is a time window that starts at the moment the first train enters the stabling yard (obtained from the schedule for that stabling yard) and ends at the moment the last train needs to start the service process in order to be finished the moment it needs to leave the stabling yard according to the schedule. In the case of Eindhoven the model calculated a time window of 10,39 hours (10 hours and 23 minutes). From the schedule it can be observed that the first train leaves active service at 18:09 and the last train enters at 9:11. This gives a window of operation of 15 hours and 2 minutes. The model calculates a total duration of the service process for the last train of 277,54 minutes or 4,63 hours, as can be observed in table 7. This table also shows the durations used to determine this.

Table 7: Calculated durations for different process elements in Eindhoven

Average duration last train	Duration in minutes	Duration in hours
Exterior washing	27,06	0,45
Service main (takt time)	90	1,50
Additional service	45	0,75
Buffer	11,32	0,19
Shunting movement	17,36	0,29
Total duration calculated	277,54	4,63
Model output	277,57	4,63

For the duration of exterior washing the average calculated train length in Eindhoven of 165,2 meters and a percentage of trains that require a change of direction of 100% are used, leading to an average time to wash a train of 27 minutes. For the additional service duration, the standard average is used, as the last train might require additional servicing and must be finished on time. An average length of all routes of 2498,4 meters and a percentage of routes requiring a change of direction of 56,5% are calculated from the route database. For the calculation of the buffer time for the last train the average wait time and time waiting for another train to couple with are set at 0 minutes, as this is the last train to arrive. This means the average buffer time for the last train is equal to the minimum buffer time. It can be held at a platform track until it can enter the buffer. Table 6 shows that the manually calculated value of 277,54 using formula (4.17) is nearly equal to the model output of 277,57, with the insignificant difference being caused by rounding errors. This shows the model produces the expected value. The calculated maximum duration of a night shift is determined to be 15,03 – 4,63 = 10,40 hours. The difference with the model output is insignificant.

The 10,39 hours of operation calculated by the model concerns the absolute maximum. This requires enough trains to arrive in the buffer from the moment the first train starts the process to keep going uninterrupted. The actual arrival and departure distribution is not considered. Table 8 shows the number of arrivals and departures per hour. It can be observed that most trains arrive between midnight and 02:00. Between 18:09 and midnight the average arrival rate of trains is 2,5 per hour. Over the 10,39-hour window of operation determined by the model 31 trains arrive. Reaching full capacity in the time window requires an arrival rate of 2,98 trains per hour. The 2,5 trains per hour can be expected to be even lower in the first few hours, as some trains might have to wait for another train to couple with. Multiplying the hourly capacity by 10,39 hours therefore leads to an overestimation of the total capacity during a night shift. If the arrival pattern would be altered to better spread arrivals this value could be reached. It can therefore only be used to determine the maximum capacity that could be reached if the arrival of trains in the first hours is high enough.

Table 8: Arrivals and departures per hour at Eindhoven stabling yard

Hour	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Arrivals	9	7	0	0	0	0	1	0	0	0	0	0
Departures	0	1	0	0	0	6	7	5	3	1	0	0
Hour	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Arrivals	0	0	0	0	0	0	2	3	4	3	0	3
Departures	0	0	0	0	1	0	0	0	0	0	0	0

4.5.2 Physical stabling capacity.

The validity of the value for the physical stabling capacity as calculated by the model is assessed by comparing the data from the SSOI with the model output for all designated stabling tracks in the standard situation in Eindhoven. Table 9 shows the results. The second column shows the useful track length in meters from the SSOI dataset as used in the model, the third column how many standard carriages this translates to using the standard carriage length of 27,2 meters and the fourth column the amount of carriages the SSOI dataset says can be parked at the tracks. The table also shows the total amount of capacity this produces and reduces it with the cutting loss factor, which NS and ProRail determined to be 7%. The platform and additional stabling capacity are added in order to be able to compare it to the model result. The table shows that the model result presented in the last row is exactly equal to the calculated capacity presented in the second to last row. However, there is a difference of 5 carriages or 3,7% difference between the model output and the total capacity ProRail and NS calculated. This is due to the rounding down to full carriages per track in the SSOI, whereas the model only performs this rounding down at the end. Rounding down per track ensures the determined capacity can be reached, whereas when only rounding down at the end the chance exists that a train might not fully fit on the track. As carriages cannot be cut in half, this method increases the chance that the operational capacity matches the theoretical capacity. However, the 7% cutting loss that has been taken into account allows some margin in order to fit the trains.

The mix of train units also has an effect on the actual stabling capacity. If only long trains would use the stabling yard, filling the tracks to maximum capacity becomes more difficult compared to a situation with only short trains for example. This does however also depend on the track length. On average the effect of this has been included in the cutting loss factor, but it depends on local characteristics to what extent this value is accurate. As the model estimates the maximum capacity, it only rounds down at the end in order to show what could potentially be possible, taking the standard cutting loss into account. In some situations an extra carriage would fit, so both methods are not fully accurate. The actual capacity is therefore likely somewhere in the middle between the two values found. Furthermore, the model still provides a usable estimate when comparing different scenarios for 100% servicing, as both scenarios use the same method.

Table 9: Result comparison

Track	**Useful length SSOI (m)**	**Number of standard carriages**	**Number of carriages in SSOI**
11	208	7,65	7
12	255	9,38	9
13	340	12,50	12
14	382	14,04	14
16	496	18,24	18
41	204	7,50	7
42a	179	6,58	6
42b	106	3,90	3
43	386	14,19	14
44	434	15,96	15
45	382	14,04	14
46	337	12,39	12
Total stabling capacity before cutting loss	3709	136,36	131
Total stabling capacity after cutting loss	3449,37	126,82	121
Extra capacity	380,8	14,00	14
Total capacity	3830,17	140,8150735	135
Model output	3830,2	140	

4.5.3 Main service capacity.

The validity of the model results for the main service capacity is also determined by comparing the model output with the SSOI data. It is however not as straightforward as the physical stabling capacity. Assumptions have been made to convert the length of the tracks into a service capacity per night. First, the physical capacity is converted to capacity per hour by dividing it by the takt time. In this study the takt time is set at 90 minutes. It is assumed that NS provides enough personnel to finish servicing within the takt time in 92% of the cases. This percentage does not have an influence on the main service capacity, as trains are moved to an additional service track if servicing is not completed. A lower takt time would increase the service capacity, but it would require more personnel and could increase the percentage of trains that cannot be serviced within the set takt time, Certain (maintenance) tasks have a minimum duration, so a lower takt time decreases the opportunity to catch up on delays. The validity of the assumptions regarding the takt time is difficult to determine. Estimates made by NS in Zwolle have been used in this model. As 100% servicing is a new concept, it has not been implemented on an actual location yet. Therefore there is no reference available to determine the validity of these assumptions.

The main service capacity is determined by dividing the sum of the length of the service tracks by the takt time and multiplying it with the window of operation as discussed in paragraph 4.5.1. This method of calculation determines the absolute maximum capacity given the takt time. It can only be reached if on average the full length of tracks is used at once, taking the 7% cutting loss into account. As is the case with the physical stabling capacity, the extent to which the theoretical maximum capacity can be reached depends on the length of the tracks and the train mix. It might be necessary to service two or more trains on one track at the same time. Compared to the physical stabling capacity, it is less likely that the 7% cutting loss factor is accurate. This is due to the fact that the amount of service tracks needed is much smaller compared to stabling tracks (at equal capacity and track length) and the track the next train has to go to is fixed, as this is the only track where space is available. The chance a train does not fit therefore increases. Another requirement to achieve the determined capacity is to move trains as far forward on the track as possible. If two trains are serviced at the same time, the second one has to move forward during servicing when the first train is finished in order to allow the next train to be serviced behind it. This would take some time out of the takt, as servicing has to be halted for safety reasons. If a change of direction is needed on the service track, moving up is impossible. The theoretical main servicing capacity can therefore only be achieved if several important infrastructural and operational characteristics are optimal, which is unlikely to be the case.

Table 10 shows the comparison between the main service capacity determined by the model and the capacity that is derived from the SSOI data. It can be observed that, as is the case with the physical stabling capacity, the model overestimates the capacity due to not rounding down the amount of carriages per track. This causes a difference of 2,7% between the calculated value of 457 carriages from the SSOI data and the model output of 469,78. Apart from that the model output corresponds to the expected value. The value of a window of operation of 10,39 hours has been used here, so if the arrival pattern of trains is not high enough in the first hour, the model would overestimate the capacity even further.

Table 10: Comparison main service capacity

Track	**Useful length SSOI (m)**	**Standard carriages**	**Standard carriages night**	**SSOI carriages**	**SSOI carriages night**
129	587	21,58	149,48	21	145
130	559	20,55	142,35	20	139
131	452	16,62	115,10	16	111
132	385	14,15	98,04	14	97
			0,00		0
Total capacity after cutting loss	1844,19	67,80	469,64	66	457
Model output			469,78		

4.5.4 Additional service capacity

The model estimates the additional service capacity in the same way as the main service capacity, with the exception that a percentage of trains that require additional service is used and the average time a train spends here is set at 45 minutes. The value of 45 minutes is a rough estimate made by the team testing 100% servicing in Zwolle, so its accuracy is unknown. It can however simply be changed in the model to assess the effect it has on the total stabling capacity. Furthermore, the model provides the maximum capacity assuming 8% of trains require additional servicing. Table 11 shows the model output compared to the calculated value from the SSOI dataset. Again, the model output only differs from the calculated value using the SSOI because of rounding down the amount of carriages, with a difference of 3,8% between the calculated value of 3060 carriages and the model output of 3180,60 carriages.

Table 11: Comparison additional service capacity

Track	Useful length SSOI (m)	Standard carriages	Standard carriages night	SSOI carriages	SSOI carriages night
15	537	19,74	3418,77	19	3290
Total capacity after cutting loss	499,41	18,36	3179,45	18	3060
Model output			3180,60		

To reach the maximum capacity the model estimates trains that require additional servicing need to arrive exactly at the moment the previous train leaves. Furthermore, no more than 8% of trains is allowed to need additional servicing. In reality every train could require additional servicing, so it could be two consecutive trains and the percentage could be much higher or lower on a specific night. If a train cannot directly go to an additional service track because it is occupied, it will have to wait on a track that could also be required for another task or for shunting movements. This would hinder the process and either reduce capacity in that night or cause delays. To take this into consideration the model provides a safety factor. This is calculated by dividing the additional service capacity by the found minimum capacity. In the initial run for Eindhoven this factor is 35. It is this large because a long track has been selected for additional servicing and the overall capacity is severely limited by the shunting capacity. The track length leads to the same inaccuracies with train types and moving up while being serviced as the main service capacity. With this value the chance of the demand for additional servicing being larger than the capacity is extremely small, but it is not impossible. Further studying of this element is required to determine what an acceptable safety factor would be.

4.5.5 Exterior washing capacity.

The exterior washing capacity is calculated using average values. It uses the average time it takes to wash the head of a train of 8,5 minutes, an average train length of 165,2 meters and a washing speed of 1 carriage per minute, as are the norms used by NS. It also uses an average walking speed for train drivers of 4 km/h for direction changes. The model calculates a capacity of 3812 meters of train or 140 carriages in a night shift with formula (4.8), using the operating window of 10,39 hours discussed in paragraph 4.5.1 in formula (4.19). This leads to an hourly capacity of 366,8 meters or 13,5 carriages. The model calculates the average time it takes to wash a train as 27,06 minutes, as can be observed in table 7, accounting for a percentage of trains that requires a change of direction of 100% obtained from the route database. In reality this capacity should be reachable, as it is calculated with norms used by NS in their estimations for the capacity. However, a look at the layout of the stabling yard in Figure 10 in chapter 5.1 shows that a direction change after washing is not a necessity, as trains could also change direction on track 35a or 40 to get to a service track. If all trains did this, the average time would drop to 26,07 minutes according to formula (4.6), which would only slightly increase the maximum capacity. The change of direction therefore only has a limited influence on the exterior washing capacity. If the routes determined by the model would be used in the actual situation the model does provide an accurate exterior washing capacity. This value is however accurate for the average train. On stabling yards where only one train type is serviced the duration of the washing of one cabin of a train could be 1,5 minutes longer or shorter or 3 minutes per train, depending on the train type. Compared to the 27,06 minutes the model found the maximum error is therefore 11%, both as underestimate and overestimate. This does limit the validity of the exterior washing capacity, but it is unlikely that a stabling yard where 100% servicing is implemented only services one type of train, which increases the chance the actual value is closer to the average value.

4.5.6 Shunting capacity.

The shunting capacity is the most difficult value to validate. It is determined using the lowest value of the capacity left on the most critical switch and the most critical track for changing direction. The route database is the starting point for the estimation of these two values. In the route database the shortest route between any pair of tracks that could require a shunting movement is stored. Often there is more than one potential route to take to get from track A to track B. In Eindhoven this is mainly but not exclusively the case for trains that require a change of direction. For example, a movement from the TWI on track 133 to the service platform on track 132 could be completed with a change of direction on track 166, 172, 35a and 40 (for visualisation see figure 11 in chapter 5.1). Furthermore, there are in total 6 options to get from track 133 to track 35a by either using track 34 or the parallel section and one of three routes through the switch complex around track 35b. The same number of options exist to get from track 35a to 132 after changing direction, leading to a total of 36 route options for this one track to change direction on. It does not make sense to evenly distribute trains over all possible routes, as some routes only add a small detour that would cause (additional) interference with normal train operations. The choice has therefore been made to calculate the length of all possible routes and perform all movements between track A and B on the shortest route available.

In order to validate the accuracy of the route determination 10 routes have been chosen from the database at random to be analysed. Appendix 3 provides an overview of all infrastructure elements passed on these 10 routes, as well as the manually calculated length and the length calculated by the model. The length of routes are estimated by taking the sum of the length of all known tracks, adding the average length of tracks without a directly known length and estimating the amount of switches and adding the average length for those. From the Inframonitor data it is determined that the average length of unknown tracks is about 25 meters and the average length of a switch section is about 27 meters. These rounded values are used in the calculation. The switch to track ratio is 0,78. The analysis of the 10 routes used as a sample shows that the length of the route corresponds well with the calculated length. The difference is maximum plus or minus 2%. Using the switch to track ratio to estimate the amount of switches on a route is therefore accurate. Drawing the routes in the figure shows that all routes seem to be following the shortest path. However, the 7th route analysed (from track 42b to 5) shows an error in the model. The route takes a left turn at a cross, which is impossible. This error has not been corrected, as it would require a different approach to the route determination algorithm, which would complicate the model. The effect of this mistake is minimal, but it should be monitored when using the model for other stabling yards. It could however have an effect on the shunting capacity on the involved cross, so if a cross is the most critical element in the shunting capacity an analysis of the routes determined by the model should be done in order to verify the validity of this result.

The shunting capacity is determined using the assumption that all movements take place on the shortest routes and train movements are evenly distributed over the different tracks assigned to a certain function. This means that available capacity is not divided to provide an optimised shunting plan. An example of this is track 166. All movements from the TWI to one of the 4 service tracks take place with a change of direction on track 166. Other options are tracks 172, 35a and 40, but these are not used for this type of shunting movement due to the route through track 166 being the shortest in all cases. This could cause the shunting capacity to be limited by the capacity of this track for direction changes, even though the rest of the stabling yard could have capacity left. Furthermore, it potentially also unnecessarily increases the use of the switches in this area, which could also lead to a reduced capacity while there is capacity left on other routes.

The results from the model are shown in table 12. It can be observed that the capacity for direction changes is smaller than the average main shunting capacity. This is average value of the shunting capacity per hour during the night shift. The maximum main shunting capacity has been added to show what would theoretically be possible if every hour would have the same shunting capacity as the highest value found. Track 166 indeed turns out to be the most critical track, as a lot of routes require a change of direction here. Track 172 for example sees no direction changes, as it requires passing two more switches compared to track 166. This is a clear shortcoming of the model that limits its uses. In reality a schedule would be made that would divide the routes over these two tracks, and in some cases also track 35a and/or 40. In the case of track 166 and 172 the remaining capacity on track 172 can be used to manually double the capacity, which would reduce the bottleneck and increase the overall shunting capacity. The model provides the use of the other tracks in order to be able to do this. It is however up to the user to verify that this is possible. It is recommended to only use this manual adaptation if the two tracks are close to each other and the other track is not used at all, because in this situation it would be clear that it can be done. In other situations the chance of errors increases.

Table 12: Shunting capacity

	Meters	Carriages
Average main shunting capacity	3300,5	121
Maximum main shunting capacity	7184,8	264
Changing direction capacity	2470,9	91

The value of the overall shunting capacity on switches also has a limited accuracy. It determines how many seconds per hour no switch on a set of routes is occupied and divides the remaining capacity over the sets of routes to determine the total shunting capacity. It does however assume a norm time of 180 seconds per occupation and does not take into account whether or not a gap between movements is large enough to perform a shunting movement. It only provides the theoretical maximum capacity, if all trains would arrive at the switch exactly 3 minutes after one another. In reality this is not acceptable, as trains do not run perfectly on time and some robustness in the train schedule is preferred in order to allow trains to reduce their delay. This problem is less of an issue during the night, when almost all occupations are caused by shunting movements. During these hours the model provides a relatively accurate theoretical maximum shunting capacity.

The estimates for the shunting capacity are only accurate if all trains follow the shortest route instead of creating an optimal shunting plan. This value can be seen as the minimum theoretical shunting capacity, which could potentially be improved by creating an optimised shunting plan. The model can provide insight in the effect of certain changes to the layout or the parameters of the service process on the overall capacity, but with a limited value.

4.5.7 Model limitations

In this chapter the validity of the results obtained from the model have been described. Several large assumptions have been used in the model that have an effect on the validity. The extent inaccuracy of the model is unclear, as the effect of some of these assumptions have not been quantified. A full-scale comparison with a model with a high validity could be done in order to do this, but this would require a large amount of scenarios to be assessed, making it very time consuming. Furthermore, no model has been found that is available for this study and qualifies to do this. As a result of this the model has several limitations, which are summed up in this paragraph.

An important limitation is that the model determines theoretical maximum capacities, only taking a standard cutting loss of 7% into account. It does not provide clear insight whether these theoretical capacities could be reached. This strongly depends on the specific layout of a stabling yard and the composition of the trains that are serviced at this location. A larger amount of tracks and a higher amount of different train types with different lengths increases the chance it can be reached, as some optimisation can be done in the order of trains going through the process and the specific track assigned. The model is therefore less suitable for small stabling yards, but these locations are unlikely to benefit from 100% servicing anyway.

The calculation of the shunting capacity contains the most assumptions. The model estimates route lengths due to incomplete data, only uses the shortest available routes, assumes all shortest routes from all tracks assigned to one process step to all tracks assigned to the next are used equally and uses the total time all switches on a route are clear to determine remaining capacity. No optimization step is included in the route determination and exact moments and durations of shunting movements are not included. The calculated shunting capacity can therefore only be reached if trains arrive at the correct time, or waiting for a red signal during a shunting movement is allowed. The operational shunting capacity is therefore likely lower than the theoretical maximum. However, the lack of an optimization step in the route determination means that shunting capacity could be increased if this is done. The validity of the calculated shunting capacity is therefore low. It can however be used to provide a global overview of the effects of the introduction of 100% servicing on the shunting capacity and assess the effect of changes made to the infrastructure or the service process.

Another limitation is the exclusion of the buffer capacity in the model. It is only estimated separately for several assumed values of average waiting time in the buffer. The buffer capacity is an important element of 100% servicing, as it deals with the inequality of the arrival times of trains and the hourly capacity of the stabling yard. It strongly depends on the arrival pattern of trains, so optimization in the train schedule could lead to a significantly larger buffer capacity. Furthermore, the buffer capacity can temporarily be increased if needed by holding the last trains at their platform tracks and using stabling tracks that are not needed yet as additional buffer tracks.

4.6 Conclusions

A model is created as a tool to estimate the stabling capacity with the implementation of 100% servicing. It is created for use on the Dutch rail network, but could be used for other locations after some adaptations. The goal of the model is to be simple and quick to use. The model takes data on the track layout, switch occupation of other train traffic and arrival- and departure characteristics of trains using the location as input, as well as several parameters related to the characteristics of the service process. It produces an estimate of all sub-elements except the buffer capacity of the total stabling capacity in order to show which element is the bottleneck. The total stabling capacity is defined as the lowest capacity of the sub-elements. The model estimates the total capacity, so it is possible that these capacities can only be achieved in an ideal situation. An example of this is the even distribution of the arrival pattern of trains, which especially influences the buffer capacity. The capacities are presented in meters of train and amount of standard carriages per night shift, as is the standard method at ProRail and NS.

The model uses several assumptions and standard values used by ProRail and/or NS to estimate the capacities. An important assumption is that NS has to provide enough personnel in order to reach a percentage of 92% of trains that are fully serviced within the takt time. This component is excluded from this study. For the shunting capacity the model uses the shortest route for all combinations of tracks that require a route. As the data is incomplete, the length of a route is estimated using some standard values. The model assumes all shunting movements will use the shortest route possible. The model therefore does not produce an optimal shunting plan where the movements of other trains are taken into account. The model also assumes all routes found between two consecutive steps of the model are used equally, so no optimization occurs. This could lead to some illogical route usage, which could negatively affect the shunting capacity. Furthermore, for some elements of the capacity the model uses average values related to the train characteristics, such as the length of trains. The buffer capacity is not calculated directly, as to many components are unknown. Instead, buffer capacity is calculated for several assumed values for the time trains on average spend in the buffer.

The validity of the model is limited due to the assumptions made. The results of the calculation of several components of the total stabling capacity corresponds well with the data of NS and ProRail. These components are the physical stabling capacity, main service capacity and exterior washing capacity. The validity of the shunting capacity is low due to the assumptions made in order to calculate it. In reality an optimized shunting plan would be created, which would use the available infrastructure as logically and efficient as possible. Deeper analysis by the user of the model of the use of infrastructure elements as determined by the model could lead to an adjusted value in some cases. Due to the low validity the model can only be used to provide rough estimates of the capacity of a stabling yard with the implementation of 100% servicing. It is more accurate when using it to determine the effect of adaptations, as the same assumptions are used in both cases.

5 Case studies

In this chapter two case studies will be performed on two separate locations. These locations are Eindhoven and Zwolle. For these two locations, the capacity with the implementation of the 100% servicing concept are determined with the model described in Chapter 4. The bottleneck(s) present in the service process at these locations are determined and adaptations to the layout of the location and/or the service process will be made to remove or reduce the bottleneck and increase the stabling capacity for this location.

5.1 Case study Eindhoven

Eindhoven is a large city in the southeast part of the Netherlands. It is an important node in the rail network, connecting the southeast with the Randstad area. To the west of the station the tracks separate into a corridor towards Tilburg, Breda and Rotterdam and a corridor towards 's Hertogenbosch, Utrecht and Amsterdam. To the east of Eindhoven, the tracks separate into a corridor towards Eindhoven and the German border and a corridor towards Heerlen, Maastricht and the Belgian border. Eindhoven is part of an important freight route from the harbour in Rotterdam towards the German Ruhr area, which leads to a lot of freight trains passing through Eindhoven.

5.1.1 Location description

The stabling yard in Eindhoven is located close to the station. It consists of three main sections. To the east of the station there are 6 tracks used for low servicing surrounded by the mainline tracks towards Venlo to the north and Maastricht to the south of the section. In figure 11 these are tracks 41 to 46. This part of the stabling yard is directly accessible from the platform tracks at Eindhoven station through the central switch complex in between. No service platforms or other equipment is present at these tracks. There are service paths, so low servicing is the only task that can be performed here.

To the south of the station there are 7 tracks that are part of the stabling yard. 15, 16 and tracks 129/14 to 133/32. Track 133 contains the only washing machine present in Eindhoven. Tracks 129 to 132 contain service platforms. These tracks can be used to perform servicing with a carousel. Tracks 15, 16 and 11 to 14 (extensions of 129 to 132) are tracks without any equipment, so only stabling is possible here. This part of the stabling yard is only accessible from the platform tracks with a change of direction. It can be reached on the east side through track 21 or 22 with a change of direction at track 166 or 172. Track 173 is not electrified and cannot be used, as all trains of NS require catenary. The section can also be reached from the west by changing direction on one of tracks 35a to 40. Tracks 36 to 39 are however part of the main line and cannot be used for this. Track 35a has a platform that is directly connected to the soccer stadium next to the tracks and is therefore only sporadically used. Direction changes are possible here.

To the southeast of the station there are several tracks that are part of the NedTrain maintenance location in Eindhoven. These are all tracks to the east of track 22 and south of track 61. These tracks are not used for standard servicing of trains and therefore do not have a function related to the service process. They are off-limits for train movements related to the service process and are therefore excluded from analysis in this case study.

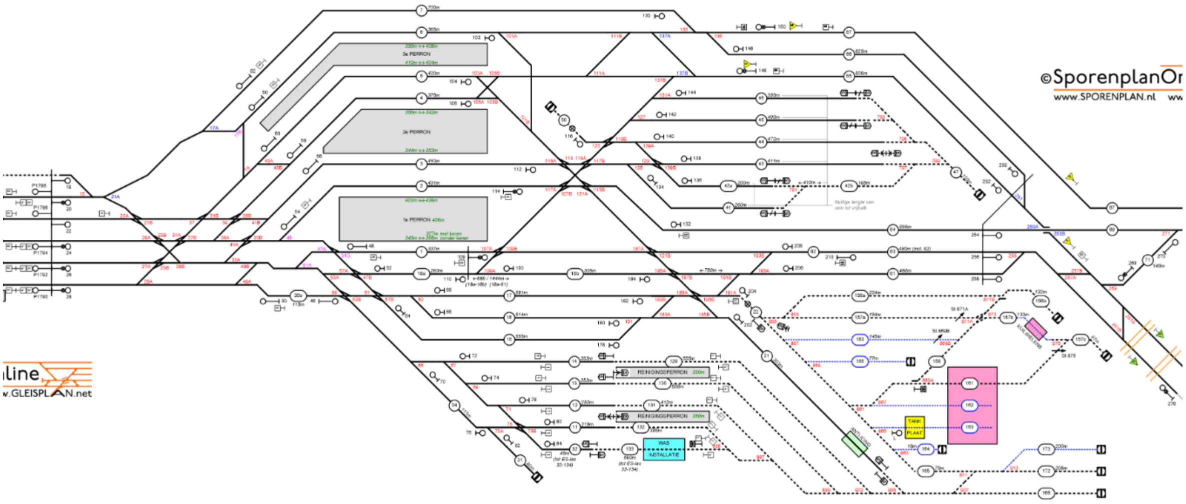

Figure 11: Schematic overview Eindhoven

Figure 12 shows a satellite image of the Eindhoven station and stabling yard. It also shows the surrounding area. As the station is quite close to the city centre, urban development has reached the borders of the tracks and stabling yard almost everywhere. Therefore expansion of the stabling yard would almost always mean demolishing some buildings to make room.

Figure 12: Satellite image Eindhoven station area

According to the most recent SSOI data the stabling yard at Eindhoven currently services 131 carriages per night. This may differ slightly per day due to disruptions in the train services. Not all of the trains that make up these 131 carriages are parked at a stabling track. According to the SSOI, 10 carriages are parked at the location of Weert, which is to the east of Eindhoven. This location does not have service capacity of its own, so the trains are serviced in Eindhoven first. Furthermore, one train consisting of 4 carriages is directly parked at a platform track instead of a stabling track. In total this means 117 carriages are parked on the yard itself.

5.1.2 Scenario 1: base scenario

The first step of the case study is to analyse the stabling capacity that could be reached without any alterations to the stabling yard. Before that can happen, some choices have to be made. Low servicing does not suite well with 100% servicing, so tracks 41 to 46 are only used for stabling. Tracks 129 to 132 are the only tracks used for the main servicing of trains. There is no track available for additional servicing at the moment. The choice has been made to assign track 15 for this task. It is the closest to the other service tracks. Some alterations would be necessary to allow servicing at this track, but they are assumed done in this case study. Because the first step after trains leave the buffer is exterior washing, tracks 166, 172 and 21 are chosen as buffer tracks. At the moment only tracks 166, 172, 35a and 40 are allowed for direction changes, as changing direction on the main line (tracks 36 to 39) is considered a safety risk. This would cause tracks 166 and 172 to have a double function.

The results the model provides can be found in table 13. It shows that the maximum amount of carriages that can be serviced at Eindhoven with the process set up as described above is 91 carriages per night. This is significantly less than the 131 carriages that are serviced in Eindhoven now. It is clear that the shunting capacity is the limiting factor. Specifically, the capacity to change direction is the bottleneck in the process. Track 166 is the track with the lowest capacity to change direction. However, it is also important to look at the buffer capacity. Table 14 shows the buffer capacity at different values for the average time trains spend in the buffer and the additional time trains spend in the buffer waiting for another train unit to couple with. It can be observed that the only combination of settings for which the buffer capacity is not the bottleneck in the service process is when both parameters are 0. This would mean all trains would leave the buffer as soon as the direction change is completed. This is only possible when the arrival pattern of trains is set up in a way that the time between arrivals is constant and the arrival rate is equal to the amount of trains the rest of the process can handle. This way, trains can never couple with another train unit, which is required in 20% of the cases. It is therefore safe to assume the buffer capacity is the bottleneck. This would mean the actual capacity is even lower than the value found by the model.

Table 13: Model results for base scenario

	Meters	Carriages
Total service capacity	2470,9	91
Stabling capacity	3830,17	141
Main service capacity	12778,7	470
Additional service capacity	86512,4	3181
Exterior washing capacity	3812,2	140
Shunting capacity	2328	91
Average main shunting capacity	3300,5	121
Maximum main shunting capacity	7184,8	264
Changing direction capacity	2470,9	91

Table 14: Buffer capacity with different parameters in meters

T_wait \ T_couple	*0*	*15*	*30*	*45*	*60*
0	3745,9	1818,4	1200,6	896,2	714,9
10	1989	1272,7	935,7	739,8	611,8
20	1354	978,9	766,6	629,9	534,6
30	1026,3	795,3	649,2	548,5	474,8
40	826,3	699,7	563	485,7	427

The actual capacity is further reduced by the fact that track 166 is used for both the buffer and changing direction. Track 166 is the most critical track from the set of tracks where a change of direction is allowed. It therefore has to be used at maximum capacity in order to reach the maximum main shunting capacity. Track 166 makes up about a third of the buffer capacity. If the buffer capacity was exactly known a division could be found that would lead to the maximum capacity for both elements together.

It is worth noting that the model chooses the shortest route for each combination of starting and ending tracks. It therefore does not take into account capacity that is already used. An example of the limitation this brings is that track 166 handles a lot more shunting movements than track 35a and 40 on the other side of the stabling yard. Track 172 does not handle any shunting movements at all. The model uses track 166 for almost all shunting movements that start and end on the southern part, because the routes are shorter. If it would divide routes between these three tracks the capacity for changing direction would increase.

5.1.3 Scenario 2

The base scenario shows that adaptations are needed to improve the shunting capacity, especially at the southern part of the stabling yard. The base scenario also showed that the servicing capacity was much larger than the total capacity of the stabling yard. For this reason only two tracks are used as main servicing tracks. These are track 131 and 132. Additional servicing is relocated from track 15 to track 130. This track has a service platform available and it is closer to the other service tracks. Tracks 15 and 129 lose their functions. In this scenario they are used as stabling tracks.

The main problems of scenario one were the buffer capacity and the shunting capacity on the east side of the southern part of the yard. To increase buffer capacity the length of tracks 166 and 172 is increased by 100 meters each. According to the aerial overview in figure 8 this requires constructing a viaduct over the road, which would be a costly but not impossible option. Furthermore, tracks 166 and 172 are no longer used for changing direction. This way the buffer capacity is not limited by shunting movements. In order to increase the capacity for changing direction a new track is constructed on the south side. It is named track A2. It connects to switch A1, which is placed between switches 895 and 897. This way half of the main service tracks can be reached from the TWI through this track, while to get to the other one the direction has to be changed on track 35a or 40. This should lead to a better distribution over shunting tracks. Track A2 gets a length of 200 meters, although this does not have much influence as the track is only used for shunting movements. According to the satellite overview there is some available space to construct this track.

Table 15: Model results for scenario 3

	Meters	Carriages
Total service capacity	1652,7	61
Stabling capacity	4875,5	179
Main service capacity	5388,3	198
Additional service capacity	89965	3308
Exterior washing capacity	4110,7	151
Shunting capacity	1652,7	61
Average main shunting capacity	2464,8	91
Maximum main shunting capacity	7605,8	280
Changing direction capacity	1652,7	61

Table 15 shows the results of the model for this scenario. It is clear that the changes have not been beneficial compared to the previous scenario, as the total stabling capacity has dropped to just 61 carriages. This is due to the lowered capacity for changing direction. It is clear that the location of the switch connecting to track A2 has caused track 35a to be used much more frequently, causing this track to become the bottleneck. It is worth noting that the model favours track 35a over track 40, which means this track has capacity left. Table 16 shows the buffer capacity for different average time values. It shows that the values need to be quite low in order for the buffer capacity not to be the main bottleneck, which means the arrival process has to be well distributed over the night.

Table 16: Buffer capacity with different parameters in meters

T_wait \ T_couple	*0*	*15*	*30*	*45*	*60*
0	3460,1	1949,2	1356,8	1040,5	843,8
10	2102,2	1429,2	1082,6	871,3	729
20	1509,7	1128,2	900,6	749,4	641,7
30	1177,8	931,9	771	657,5	573
40	965,5	793,8	674	585,6	517,7

5.1.4 Scenario 3

The final scenario that is analysed is an adaptation of scenario 2. The division of tracks for certain tasks remains the same, with the addition that an additional buffer track is constructed to the south of track 166. This track is named B1. It has a useful length of 370 meters, equal to the increased length of track 166 (tracks 166 and 172 keep their extension of 100 meters). Switch B1 is positioned between switches 905 and 907. It is therefore only accessible from the platforms through track 21. The switch connecting track A1 to the rest of the stabling yard has been moved. It is now positioned between switch 899 and 903, which enables all movements from the TWI to the service tracks and from the service tracks to the additional service track to change direction here. Furthermore, an additional track (B2) is constructed directly to the south of track 35a to increase the capacity for direction changes. It connects to switch B2, which is located between switch 25A and 49A. This is done for two reasons. Not all routes can take place through this track, because not all platform tracks can be reached. Because it is closer to the stabling yard, it will be preferred over track 35a. This way a better division between the tracks is created. It also ensures that track B2 does not reach the platform at track 35a. There would be no space to construct a track here. In the location were the new track is constructed now there also isn’t much space. A viaduct would have to be widened and potentially a building close to the tracks would have to be demolished. This is a very costly alteration, but space around Eindhoven is scarce and shunting tracks are the main bottleneck for capacity.

Table 17 shows the results of the model run for this scenario. Even though additional tracks were constructed for the sole purpose of changing direction, this aspect of the capacity is still the bottleneck in the process. Track A1 is the biggest bottleneck, closely followed by track B2. The construction of track B2 did have a positive effect on track 35a, as a better division is created between the tracks. The fact that tracks B2 and especially 35a have shunting capacity left indicates the actual shunting capacity could be higher if some of the trains changing direction on track A1 would do so on one of the other tracks. By doing this the actual shunting capacity could approach the stabling capacity that is reached with the current, non-100% servicing process. It is however clear that Eindhoven is a challenging location for 100% servicing, as the layout causes the need for a lot of direction changes while the infrastructure cannot handle these movements.

Table 17: Model results for scenario 4

Kolom1	Meters	Carriages
Total service capacity	2974,2	109
Stabling capacity	4875,5	179
Main service capacity	5396,4	198
Additional service capacity	90101,3	3313
Exterior washing capacity	4116,9	151
Shunting capacity	2974,2	109
Average main shunting capacity	6226,1	229
Maximum main shunting capacity	10767	396
Changing direction capacity	2974,2	109

Table 18: Buffer capacity with different parameters

T_wait \ T_couple	*0*	*15*	*30*	*45*	*60*
0	4793,7	2700,5	1879,7	1441,6	1169,1
10	2912,5	1980	1499,8	1207,1	1010
20	2091,6	1563	1247,7	1038	889
30	1631,7	1291,1	1068,1	910,8	793,9
40	1337,6	1099,8	933,7	811,2	717,2

5.1.6 Conclusions

From the 3 scenarios that have been assessed in this case study it becomes clear that Eindhoven as a stabling location is not well suited for the implementation of 100% servicing. The fact that it has service platforms available is a positive aspect, but the infrastructure cannot handle the amount of additional movements that a change to 100% servicing causes. The southern part is only accessible from the platforms and northern part with a change of direction, as almost all tracks are parallel to the platform tracks. This means movements within the southern part also require a change of direction in a lot of cases. The area around the station is quite heavily developed, so space for additional tracks is rare. Only to the south of track 166 there is some space available. Increasing the amount of tracks for changing direction on both sides of the southern part does increase the capacity compared to the base situation with 100% servicing, but reaching the current capacity with a small number of adaptations seems impossible. Changing the division of tracks for the service process can also have a positive effect on the capacity, but not to the extent of the adaptations made in scenario 3. Overall Eindhoven is a location were the implementation of 100% servicing is more likely to decrease the stabling capacity than increase it.

5.2 Case study Zwolle

Zwolle is an important node in the Dutch rail network. It connects the northern provinces to the Randstad area and the eastern part of the country. To the east of the station the tracks separate into a corridor towards Deventer, Zutphen and Arnhem and a corridor towards Groningen, Leeuwarden and Emmen. The last of these corridors splits into three separate corridors a small distance from Zwolle, with one corridor towards each of the three cities mentioned. To the west of the station the tracks separate intro a corridor towards Lelystad, Amsterdam and Schiphol Airport and a corridor towards Apeldoorn, Amersfoort and Utrecht. Directly east of the station there is also a connection to a small local line towards Kampen. Zwolle is not on any main freight corridors, but it does receive some freight trains going to the northern provinces. An important difference with Eindhoven is that in Zwolle NS is not the sole operator. Other operators are also active at the station and also service trains here. Therefore only a part of the total stabling yard is dedicated to NS.

5.2.1 Location description

The stabling yard in Zwolle consists of three main parts. Figures 13 and 14 provide a schematic overview of the location. Due to the distance between the station and two part of the stabling yard and the third part the overview is provided in two separate figures. Figure 13 connects on the left side to the right side of figure 14. The main section of the stabling yard is located to the southeast of the station. This area is dedicated to NS, with the exception of the refuelling tracks. The TWI is located on track 98. Tracks 90 and 91 are located besides a service platform, where services are performed with a carousel process. Track 95 also provides service possibilities, while track 96 has aerial platforms and a system to check the functionality of the ATB system of trains. The other tracks are either stabling or shunting tracks. To the north of the main section there is Zwolle Goederenemplacement (Zlge). This is a freight yard that has partially been turned into a stabling yard. There are no tracks where trains can be serviced. NS can park trains at tracks 19, 20, 23, 18b and 18c. Track 23 is however not electrified, and since Ns does not have diesel trains anymore it is ignored.

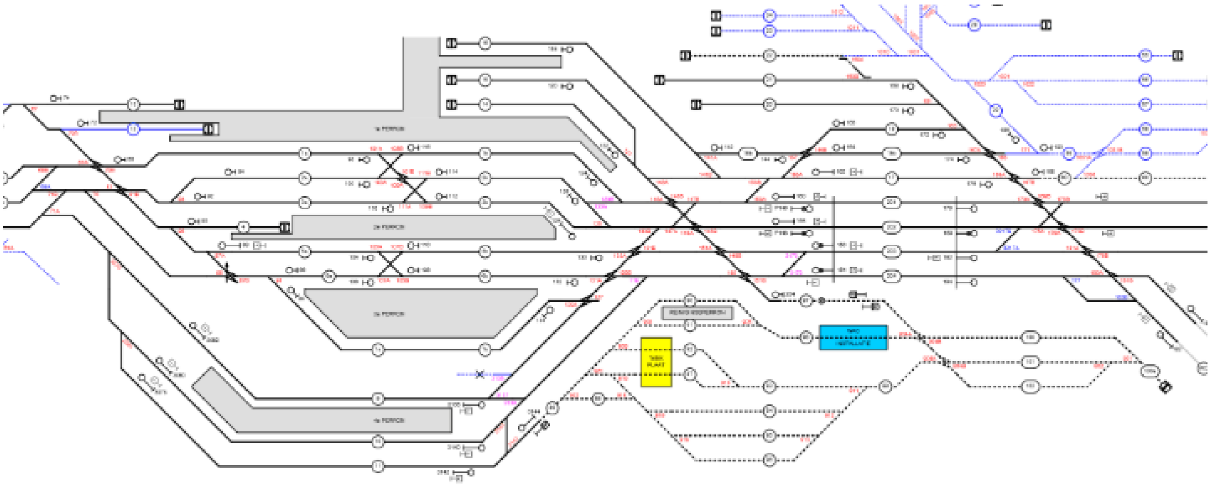

Figure 13: Schematic overview of the Zwolle station area

The third section of the stabling yard is Zwolle RGS (Zlr). It is located to the southwest of the station, several kilometres away. The schematic overview does not show this. This location contains a lot of tracks, but only tracks 31, 32, B1, B3, B4 and B6 are dedicated to NS servicing is possible at the 4 B-tracks and is sort of done in a carousel process to allow the use of the other two tracks without service equipment as stabling tracks. All other tracks are either dedicated to other operators, freight operators or maintenance providers or are in disrepair or used to store train units on the nomination to be demolished.

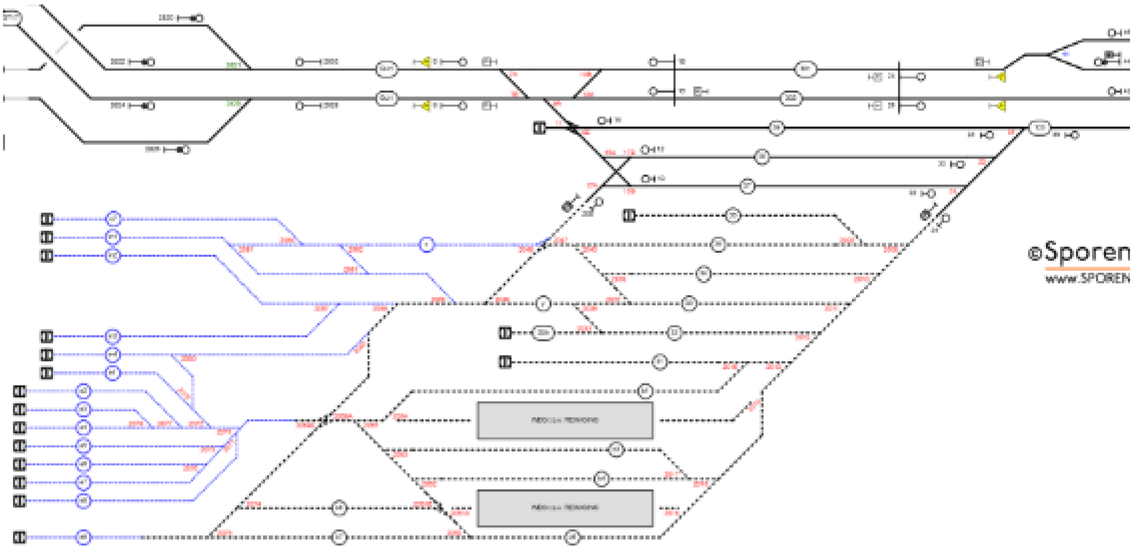

Figure 14: Schematic overview of the Zwolle RGS stabling yard

Figure 15 shows the satellite overview of the stabling yard in Zwolle. It is clear that the third section is quite some distance away from the other two, with a tight bend in between. The third section is located outside of the city, which means there is less concern about noise production and more space to expand the location.

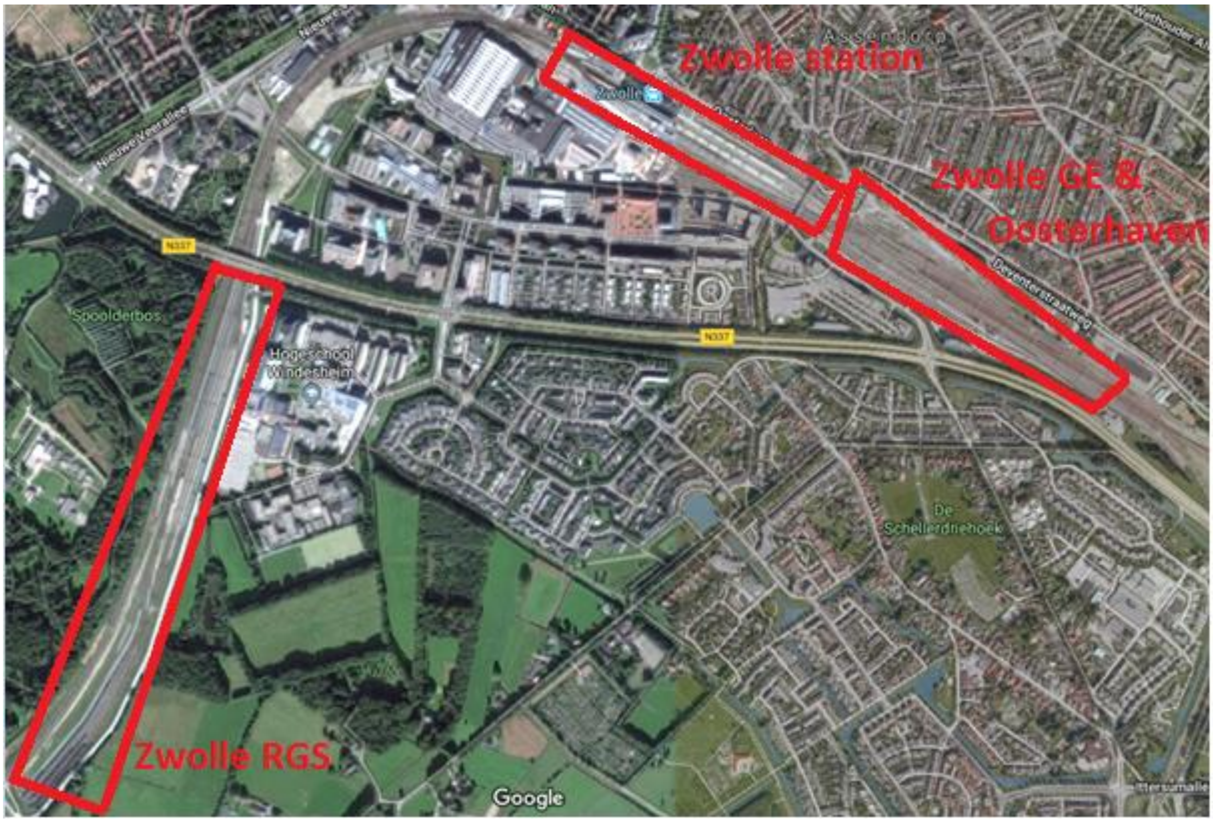

Figure 15: Satellite image of the Zwolle station area

In the current situation Tracks B1 to B6 are used as service tracks where trains are also parked. Tracks 31 and 32 are pure stabling tracks. Trains parked here are serviced at tracks B1 to b6. Trains parked here are usually not washed, as the TWI is some distance away. To the east of the station track 98 is equipped with a TWI. Tracks 90 and 91 have a service platform. These tracks can be reached from the TWI directly. Track 96 is a service track equipped with an aerial platform and an ATB measurement system. Tracks 100, 101 and 95 are used for stabling. The other tracks at the southeast part are shunting tracks or tracks that are not assigned to NS. To the northeast of the station tracks 18b, 18c, 19, 20 and 23 are assigned to NS. These tracks are purely for stabling, so no service takes place here. Trains are serviced at tracks 90 and 91. Track 23 is not electrified, and since NS does no longer operate diesel trains this track is not used in this case study. Stabling at platform tracks is not used in Zwolle at the moment.

5.2.2 Scenario 1: base scenario

In the first scenario the tracks where certain tasks are performed are kept as close to the current situation as possible. There are however some differences. Tracks 100, 101 and 102 are designated as buffer tracks. The TWI is kept at track 98. All servicing is done on a service platform alongside tracks 90 and 91. Tracks B1 to B6 are turned into pure stabling tracks, so no servicing will take place here. Tracks 18b, 18c, 19 and 20 are kept as stabling tracks. Track 95 is also designated as stabling track, while track 94 is allocated to another operator, so this track has no function for NS. Additional servicing is performed at track 96, as there is equipment and an aerial platform available at this track. In order to facilitate shunting movements, changing direction is allowed at tracks 11, 37 and 60a. Because track 1a cannot be directly reached from Zwolle RGS, track 2b can be used for direction changes towards track 1a.

There are several combinations of tracks that cannot be connected with just one change of direction. These are tracks 18b and 20, which can only be reached from the service tracks with two changes of direction. As the model does not allow this, these routes are not used in the capacity determination. As a result, the physical stabling capacity is slightly overestimated, unless real life operations would allow shunting movements with two direction changes.

Table 19: Model results for scenario 1

	Meters	Carriages
Total service capacity	3419,6	126
		0
Stabling capacity	3419,6	126
Main service capacity	4063,7	149
Additional service capacity	37051	1362
Exterior washing capacity	4725,7	174
Shunting capacity	7024	258
		0
Average main shunting capacity	7024	258
Maximum main shunting capacity	17282	635
Changing direction capacity	32197	1184

Table 19 shows the results obtained from the model for the base scenario. Unlike the stabling yard in Eindhoven, the shunting capacity is not the limiting factor in Zwolle. It turns out the physical stabling capacity is the limiting factor with 126 carriages, closely followed by the main service capacity. The low requirement for direction changes and the possibility to determine routes that use the same infrastructure as little as possible allows for a high stabling capacity. The current capacity of the stabling yard in Zwolle has been determined to be 115 carriages. A reduction of 4 carriages due to operational choices and a slight overestimation of the stabling capacity by the model cause this difference. Table 20 shows the buffer capacity for different values of the average time trains spend waiting in the buffer and waiting for another train unit to couple with. It can be observed that the buffer capacity is a much bigger bottleneck than the stabling capacity, as the buffer capacity is already much lower if both values are set to 0 minutes. This would indicate that all trains can leave the buffer as quickly as possible, no trains have to wait for another train unit and the arrival pattern of trains is perfectly distributed. This is very unlikely, so the actual buffer capacity will likely be a lot lower than 2657 meters. It is likely that it is not higher than 1600 meters, reducing the total capacity by more than 50%. The buffer is clearly the biggest bottleneck, mostly caused by the use of relatively short tracks and a need for a direction change in the buffer of 100%.

Table 20: Buffer capacity for different parameters

T_wait \ T_couple	*0*	*15*	*30*	*45*	*60*
0	2656,7	1476,7	1022,5	782	633,1
10	1594,8	1077,8	813,9	653,9	546,4
20	1139,4	848,6	676	561,8	480,6
30	886,2	699,7	578,1	492,5	428,9
40	725,2	595,3	504,9	438,3	387,3

5.2.3 Scenario 2

In scenario 1 it was clear that the buffer capacity was the biggest bottleneck, limiting the total capacity. In this scenario the buffer capacity will be increased. This is done by adding tracks 2a and 2b to the buffer. These tracks are especially useful to provide buffer capacity for trains coming from tracks 1a, 1b, 3a and 3b, as the two additional buffer tracks can be reached with a simple movement. Tracks 100 to 102, which are used as buffer tracks, are elongated by 100 meters each. This is done because the addition of tracks 2a and 2b will probably not provide enough additional buffer capacity. There is some space available to increase the length of these tracks, but is does require the removal of track 100a and the switches in between. Tracks 100 to 102 become tracks with a buffer stop at the end. Track 100a was too short to be of any use anyways.

Table 21 shows the results provided by the model. As the only changes made concerned the buffer, the results are similar to scenario 1. However, adding tracks 2a and 2b to the buffer does have an effect on the shunting capacity. Shunting movements might take place at different locations and more direction changes are needed as the TWI cannot be reached directly from tracks 2a and 2b. This causes a drop in shunting capacity of 84 carriages, but the shunting capacity is still higher than the physical stabling capacity.

Table 22 shows the calculation of the buffer capacity for different parameters regarding waiting time. It can be observed that the buffer capacity has increased significantly as a result of the changes. Some waiting time is acceptable in order for the buffer capacity to not be the bottleneck, but it is limited to 10 minutes average waiting time or 15 minutes average waiting for another train unit. This is not a lot of time, especially since the arrival pattern of trains causes a peak in the two hours after midnight. The buffer capacity is therefore likely the bottleneck, unless the arrival pattern is optimized. It might be possible to leave trains at platform tracks longer and use them as an additional buffer, but this would only apply for the last couple of trains to arrive and the tracks should not be used by freight trains or other operators.

Table 21: Model output scenario 2

	Meters	Carriages
Total service capacity	3419,6	126
Stabling capacity	3419,6	126
Main service capacity	4023,8	148
Additional service capacity	36688	1349
Exterior washing capacity	4679,4	172
Shunting capacity	4742,3	174
Average main shunting capacity	4742,3	174
Maximum main shunting capacity	12495	459
Changing direction capacity	41715	1534

Table 22: Buffer capacity for different parameters

T_wait \ T_couple	*0*	*15*	*30*	*45*	*60*
0	6924,2	3183,3	2066,6	1529,9	1214,5
10	3498,1	2194,9	1599,1	1257,7	1036,5
20	2340,2	1674,9	1304,2	1067,8	904
30	1758,2	1354,1	1101	927,7	801,5
40	1408	1136,4	952,7	820,1	719,9

5.2.4 Scenario 3

In this scenario the buffer capacity is further increased, as it turned out that this was likely still the largest bottleneck in scenario 2. The alterations to the buffer in scenario 2 are kept in this scenario and track 38 is added to the buffer. This track is located at Zwolle RGS, so it causes some lengthy additional shunting movements to get there and back to the TWI. It is also used as a passing track for freight trains at the moment, so the ability to do this is significantly reduced by using track 38 for the buffer. However, track 38 will only be needed at the peak of arriving trains and at that point passenger train traffic has almost stopped, so this should not be a big problem. Furthermore, track 38 has a substantial length to increase the buffer. The second bottleneck in the stabling capacity is also improved. A total of 10 carriages of additional stabling capacity is created at two platform tracks. A train of 4 carriages and one of 6 carriages can be parked there to immediately start scheduled service in the morning. The exact tracks are not specified, as this might change on a daily basis due to other train movements and track maintenance.

Table 23 shows the results provided by the model. It is clear that the physical stabling capacity has increased by 10 carriages to 136 carriages. The physical stabling capacity is however still the main bottleneck. Adding track 38 to the buffer has had an effect on the shunting capacity. It has dropped from 174 to 165 carriages due to the additional shunting movements. Switch 35, which is the only entrance to and exit from Zwolle RGS, is the most critical switch. The decrease is however not enough to cause the shunting capacity to be the limiting factor.

Table 23: Model output scenario 3

	Meters	Carriages
Total service capacity	3691,6	136
Stabling capacity	3691,6	136
Main service capacity	4021,9	148
Additional service capacity	36670	1348
Exterior washing capacity	4677,1	172
Shunting capacity	4488,7	165
Average main shunting capacity	4488,7	165
Maximum main shunting capacity	11750	432
Changing direction capacity	39656	1458

Table 24 shows the calculation of the buffer capacity for different time values. Adding track 38 to the buffer has significantly increased the buffer capacity, as was the expectation. Longer average waiting times are now allowed in order for the buffer to not be the bottleneck. The increase is however limited, which indicates that the buffer capacity will still be the bottleneck if the arrival pattern of trains features a peak around midnight. Either the arrival pattern has to be optimized or some trains arriving during the peak have to be temporarily held at a platform track or a mainline track.

Table 24: Buffer capacity for different parameters

T_wait \ T_couple	*0*	*15*	*30*	*45*	*60*
0	8911,6	4272,5	2809,8	2093,2	1667,8
10	4678,4	2979,8	2186,1	1726,3	1426,3
20	3171,7	2287,7	1789	1468,8	1245,9
30	2399,1	1856,4	1514	1278,2	1106
40	1929,2	1562	1312,3	1131,4	994,3

5.2.5 Conclusions

From the base scenario it becomes clear that the track layout of the stabling yard in Zwolle is much more suitable for the implementation of 100% servicing. In Eindhoven the shunting capacity was a mayor limiting factor, but in Zwolle it has not been (one of) the bottlenecks in any of the scenarios. This has to do with the fact that in Zwolle the consecutive steps of the model are located in a good order, which significantly reduces the need for a change of direction. It also reduces several sets of routes requiring the use of the same switches, which increases the shunting capacity. Instead of the shunting capacity, the buffer capacity turned out to be the main bottleneck in Zwolle. The three relatively short tracks turned out to be insufficient to handle the amount of trains the next bottleneck could handle. The need for a direction change on all buffer tracks also negatively affects the buffer capacity. In order to remove this bottleneck, tracks 100, 101 and 102 have been lengthened by 100 meters each and tracks 2a and 2b were used as an additional buffer. This significantly increased the buffer capacity, but not enough to be able to say it is not the bottleneck. Adding track 38 to the buffer as well increased the buffer capacity to a level it might not be the main bottleneck, but only if the arrival rate of trains is distributed over the night enough. It might also require holding trains at their platform tracks longer at the busiest moments. The physical stabling capacity was the next bottleneck, even after adding a capacity of 10 carriages at the platform tracks as improvement in scenario 3. If the desire exists to further increase the stabling capacity at Zwolle, the physical stabling capacity has to be increased. To do this, there are several unused tracks available at Zwolle RGS, but some of these are in disrepair, not electrified, or both, so some funding is required to achieve this. Furthermore, switch 35, which is the only way in and out of Zwolle RGS, is already the most critical element in the shunting capacity. Adding stabling capacity at Zwolle RGS will therefore reduce the shunting capacity, so additional measures to and around this switch would be required.

6 Conclusions and recommendations

In this chapter the conclusions from this study are presented. Furthermore, recommendations are made about potential future research and improvements of this study. In paragraph 6.1 the answer is provided to the research question:

How can the stabling capacity of a stabling yard be estimated with the implementation of 100% servicing?

6.1 Conclusions

The current stabling process and the 100% servicing concept differ from each other on several aspects. In the current stabling process trains are only serviced when the time window for a task is reached. In the 100% servicing concept certain tasks are performed every time a train reaches a stabling yard, such as exterior washing and checks of the interior of a train. This increases the quality of the product that NS can provide to its customers. In the current stabling process trains are often parked on a certain track, after which servicing tasks are performed here. In the 100% servicing concept all trains will move between tracks where certain tasks are performed. This should increase the efficiency of personnel and equipment, but causes additional shunting movements compared to the current process. The expected increase in capacity should come from the more optimal use of stabling tracks.

In this study a model has been created that estimates the stabling capacity for a certain location with the implementation of 100% servicing. It calculates an estimate for five parts of the total capacity: the physical stabling capacity, service capacity, additional service capacity, exterior washing capacity and the shunting capacity. The estimates are calculated using standard units as used by NS, as well as data from the track layout database of the location, the switch use by other trains at the location, the standard current use of the location and data on train types. It uses a simplified method to determine routes between two tracks based on the estimated route length and assumes equal division of movements over potential routes. A window of operation is determined for a specific location by assessing the arrival times of trains. This is used to convert the hourly values of some capacities into the total amount per night.

The model can be used to roughly assess the effect the implementation of 100% servicing has on the capacity of a stabling yard. It can also provide insight in the effect certain adaptations to the infrastructure or the service process could have. An analytical model that can incorporate the characteristics of 100% servicing is a new type of model. It provides ProRail and NS with a quick and simple way to assess the suitability of stabling yards for 100% servicing and determine the effect of adaptations. It could also be of interest for other rail operators interested in the 100% servicing concept. The model does have some limitations. It only provided a rough estimate of the capacity. The level of validity of the shunting capacity is low, mainly because the model does not create an optimized shunting plan. Capacity already used for other shunting movements is not taken into account when planning routes. The shortest route is always chosen, leading to some route sections being used exclusively, while alternatives could be available. The model should therefore not be used as a tool to make a decision, but only as a first indicator for the suitability of a stabling yard for 100% servicing. Another limitation is the buffer capacity. It has not been directly included in the model, as there was too much uncertainty regarding this aspect of the total capacity. In theory buffer capacity isn't even needed if all trains arrive at the exact moment they can move through to the next process step and all trains leave active service in the correct composition, but in reality there is a peak of arrivals after midnight that the buffer needs to deal with and only about 80% of trains leave active service in the correct composition.

The main conclusion that can be drawn from the case study in Eindhoven is that this location is not very suitable for 100% servicing. None of the 3 scenarios that were analyzed showed an increase in stabling capacity compared to the current situation. In the base scenario the capacity was reduced by about a third. Changing the function of tracks and constructing additional tracks for shunting movements did raise the stabling capacity, but not to the level of the current situation. The main problem in Eindhoven is clearly the fact that almost all routes to, from and on the southern part of the stabling yard require a change of direction, while the capacity to do this is far insufficient. The space to increase this capacity is also limited due to urban development close to the tracks.

The case study for the stabling yard in Zwolle has revealed that this location is much more suitable for 100% servicing than Eindhoven. This is due to the fact that the tracks assigned to certain tasks of the process are located in a way that allows direct movements without a change of direction. It also limits the amount of routes using the same switches. A similarity between Zwolle and Eindhoven is the fact that the buffer capacity is a bottleneck in both. The buffer is very important for 100% servicing, as the arrival of trains is not evenly distributed and some trains have to wait for another train unit to couple with. A solution for this would be to hold trains at platforms if possible and potentially use some stabling tracks as buffer at the beginning of the night shift. The next bottleneck in Zwolle is the physical stabling capacity, which could be increased at Zwolle RGS. This would however have an effect on the shunting capacity, as switch 35 is the only way in and out for most of the location.

6.2 Recommendations

6.2.1 Recommendations for users of the model

It is important to keep in mind that the validity of the results of the model is limited. The model is therefore not suitable to accurately try to determine to what extent a location could see an increase in stabling capacity from the implementation of 100% servicing. The model can provide an estimate of the effect, as well as an estimate of the effect of certain changes. It is possible to use the model to create a ranking of locations were 100% servicing could have the biggest effect on the stabling capacity. It is recommended that the model is used only as a first step in the decision process regarding the implementation of 100% servicing. It can be useful to get a rough estimate, before time and money are spend on a more extensive analysis of the potential of the location. This additional analysis can be done using a more advanced model that does create an optimized shunting plan, or it can be done using a manual simulation where a night shift is simulated by moving trains over a track overview of the location.

The model is also usable for stabling yards outside of the Netherlands. Several parameters used in the model might have to be changed, such as the standard carriage length or shunting speed for example. It is recommended that the input data is selected thoroughly, as the model requires complete datasets in the correct format. If the input data is not available in the correct format, it is recommended to alter the input data, rather than altering the model to be able to use the available input data. This is because the model is written to handle data for the Netherlands and it uses the format throughout the model.

6.2.2 Recommendations for ProRail and NS

The limited available stabling capacity and the rapidly expanding fleet of NS require a quick response in order to prevent a capacity shortage in the coming years. Construction or expansion of stabling yards is unlikely to provide a large enough capacity increase, so other solutions have to be found. The results from the case study for Zwolle shows that 100% servicing can potentially lead to an increase of the total stabling capacity. It is therefore recommended that ProRail and NS continue with the development of this concept. Additional analysis of current locations is needed in order to be sure 100% servicing will cause a capacity increase at these specific locations. The results from the case studies show that shunting capacity is an important element of the total stabling capacity. It is strongly influenced by the specific track layout. Further analysis could be done into the exact infrastructure characteristics that influence the shunting capacity.

Another recommendation to ProRail and NS is the availability of complete and accurate datasets. The data for the current use of stabling yards had to be manually created for the use in this study. The infrastructure data obtained from the Infra-atlas turned out to be incomplete. Several tracks had names that did not match other data sources and for some tracks the boundary elements were missing, not an infrastructure element (but rather a signal, stop sign or derail) or not consistent. A beginning and ending boundary element was presented, but it was unclear what side of the track was the beginning and what side the end. It was inconsistent and appeared not to follow specific rules. A complete and consistent dataset would be very useful for future use in similar studies that require these boundary elements.

6.2.3 Further research

The main areas where more research could be done are the shunting and buffer capacity. A more detailed analysis of the accuracy of the estimated shunting capacity would provide a better understanding of the validity of the model. A study could be done were a full-scale model that creates an optimized shunting plan is compared to the model created in this study. It would be best if this is done for different locations and several scenarios per location, with the model settings as equal as possible. An improvement that could be made to this model is to implement a method to divide routes over the shunting tracks, although the best way to do this would be to create an optimized shunting plan, which is precisely what this model lacks to simplify it.

Further research could also be done into the buffer capacity. In this study the buffer capacity has not been properly defined. Not enough data was available regarding the exact demand for buffer capacity, as it depends on several factors with high uncertainty. In reality, A lot of trains leave active service between midnight and 2 am, so a sufficient buffer capacity is important for 100% servicing. But trains could be held at their platform track if it is not needed for another train, or they could temporarily be parked at other tracks that are not yet needed, such as stabling tracks. The high flexibility and lack of clear planning made it difficult to include in the model, which is why it wasn't. It could possibly be an improvement made in the future.

Bibliography

Assad, A. (1979). Models for Rail Transportation. *Transportation Research*, 205-220.

Cicerone, S., D'Angelo, G., Di Stefano, G., Frigioni, D., & Navarra, A. (2007). Robust Algorithms and Price of Robustness in Shunting Problems. *ATMOS*, 175-190.

Di Stefano, G., & Koci, M. (2004). A Graph Theoretical Approach To The Shunting Problem. *Electronic Notes in Theoretical Computer Science*, 16-33.

Dura Vermeer. (unk.). *Resultaten van twee GHG genererende kenenanalyses van DVDI.* Retrieved from duravermeer.nl: https://www.duravermeer.nl/Portals/0/PDF/Analyse%20GHG%20genererende%20ketens%20DVDI_final%20Extern%20%281%29.pdf

Hoepel, F. (2017). *Decision support on capacity problems NS.* unk.: TU/Eindhoven; NS.

Janssens, S. (2017). *Empirical Analysis of Service Locations at NedTrain.* unk.: NS.

Lentink, R. (2006). *Algorithmic Decision Support for Shunt Planning.* Rotterdam: Erasmus Research Institute of Management.

M. Abril, F. B. (2008). An assessment of railway capacity. *Transportation research Part E 44*, 774-806.

M. Marinov, J. V. (2009). A Simulation Modelling Methodology for Evaluating Flat-shunted Yard Operations. *Simulation Modelling Practice and Theory*, 1106-1129.

Marksbery, P., Badurdeen, F., & Maginnis, M. (2011). An investigation of Toyota's social-technical systems in production leveling. *Journal of manufacturing technology management vol. 22 issue 5*, 604-620.

Ministerie van Infrastructuur en Milieu. (2015). *Concessie voor het hoofdrailnet 2015-2015.* Den Haag: Ministerie van Infrastructuur en Milieu.

NedTrain. (2017, 09 24). *NedTrain Locaties*. Retrieved 2017, from NedTrain.nl: http://www.nedtrain.nl/over-nedtrain/locaties/

NS. (2016). *NS Jaarverslag 2016.* Utrecht: Nederlandse Spoorwegen.

NS. (2016, april 6). *Pitstop voor trein levert NS 4.500 extra plaatsen op*. Retrieved from nieuws.ns.nl: http://nieuws.ns.nl/pitstop-voor-trein-levert-ns-4500-extra-plaatsen-op/

NS. (2016). *Vervoerplan 2017.* Utrecht: Nederlandse Spoorwegen.

NS. (2017, 09 20). *Verzelfstandiging en kerntaken*. Retrieved from ns.nl: https://www.ns.nl/over-ns/wie-zijn-wij/geschiedenis/verzelfstandiging-en-kerntaken.html

P.J. Zwaneveld, L. K.-P. (1996). Routing Trains Through Railway Stations: Model Formulation and Algorithms. *Transportation Science 30*, 181-194.

Pepper, M., & Spedding, T. (2010). The evolution of lean Six Sigma. *International journal of quality & reliability management vol. 27 issue 2*, 138-155.

ProRail. (2016). *ProRail jaarapportage 2016 (deel A/B).* Utrecht: ProRail.

ProRail. (2017, 09 24). *Programma Hoogfrequent Spoorvervoer*. Retrieved from ProRail.nl: https://www.prorail.nl/programma-hoogfrequent-spoorvervoer

ProRail. (2017, 09 24). *ProRail in cijfers*. Retrieved from ProRail.nl: https://www.prorail.nl/over-prorail/wat-doet-prorail/prorail-in-cijfers

ProRail; NS. (2017). *Single Source of Information v4.0 (SSOI).* Utrecht: ProRail; NS.

Schrijver, A., Lentink, R., & Kroon, L. (2008). Shunting of Passenger Train Units: an Integrated Approach. *Transportation Science vol. 42 issue 4*, 436-449.

Tomii, N., & Zhou, L. (2000). Depot shunting scheduling using combined genetic algorithm and PERT. In W. Press, *Computers in Railways VII* (pp. 437-446). Ashurst: WIT Press.

van den Broek, J., & Kroon, L. (2007). A capacity test for shunting movements. In K. L. Geraets F., *Algorithmic Methods for Railway Optimization* (pp. 108-125). Berlin: Springer.

van den Broek, R. (2017). *Train Shunting and Service Scheduling: an integrated local search approach.* Utrecht: Universiteit Utrecht.

Zeegers, S. (2017, 08 27). *Tekeningen met spoornummers en seinen*. Retrieved from Sporenplan: http://sporenplan.nl/

Zwaneveld, P., Kroon, L., Romeijn, H., & Salomon, M. (1996). Routing Trains Through Railway Stations: Model formulation and Algorithms. *Transportation Science vol. 30 issue 3*, 181-194.

Appendix 1: Facilities per service location

Location	Washing machine	Technical centre	Aerial platform	Working shaft
Alkmaar			Yes	Yes
Amersfoort			Yes	
Amsterdam Zaanstraat				
Amsterdam Watergraafsmeer	Yes	Yes	Yes	
Arnhem	Yes		Yes	
Den Haag Binckhorst	Yes	Yes	Yes	Yes
Den Helder				
Deventer				
Dordrecht				
Eindhoven	Yes	Yes	Yes	
Enkhuizen				
Enschede	Yes			
Groningen			Yes	
Haarlem				
Heerlen				
’s Hertogenbosch				
Hengelo		Yes	Yes	
Hoofddorp			Yes	
Hoorn				
Leeuwarden			Yes	Yes
Leidschendam	Yes	Yes	Yes	Yes
Lelystad	Yes			
Maastricht	Yes		Yes	
Nijmegen	Yes		Yes	
Roosendaal			Yes	Yes
Rotterdam	Yes		Yes	Yes
Utrecht Cartesiusweg	Yes	Yes	Yes	
Utrecht Landstraat				
Utrecht OZ				
Venlo				
Vlissingen	Yes			
Zutphen				
Zwolle	Yes		Yes	

Appendix 2: service requirements per train type

Type	A-check interval	A-check duration	B-check interval	B-check duration	Internal cleaning time
SGM-2	12	38	2	9	10
SGM-3	12	44	2	10	15
SLT-4	12	45	1	23	15
SLT-6	12	51	1	27	20
Flirt-3	3	40	1	18	15
Flirt-4	3	48	1	24	20
DDAR	12	68	2	18	32
VIRM-4	12	54	2	12	37
VIRM-6	12	60	2	14	56
DDZ-4	12	76	2	15	49
DDZ-6	12	90	2	18	56
ICM-3	12	61	2	8	23
ICM-4	12	64	2	11	30
DDM	12	38	2	20	37
ICR-6	1	180	N/A	N/A	44
ICR-9	1	210	N/A	N/A	62
ICR_BLX	1	150	N/A	N/A	44
ICR_DB	1	90	N/A	N/A	60
Thalys	1	150	N/A	N/A	70
ICE	1	150	N/A	N/A	70
Eurostar	N/A	N/A	N/A	N/A	N/A

Appendix 3: Route tables

	1	2	3
From	6	129	130
To	21	42a	44
Calculated length	874	2437	2730
Model output	854,8	2438,8	2748,6
Difference (%)	2,2	-0,1	-0,7
Track sections	s6-w101Av	s14	s13-s130
	w101Ar-kK_101AR-105BV	w67l-s14	s13
	kK_101AR-105BV-w101Br	w65l-w67v	w69l-s13
	w101Bv-w113/115Av	w59/53Bv-w65v	w67r-w69v
	w113/115A-KW_115AR-117AL	w53Ar-w59/53Bv	w65l-w67v
	KW_115AR-117AL-w115B/121A	w51Ar-w53Av	w59/53Bv-w65v
	w115B/121Av-w121B/187Av	w49Bv-w51Av	w53Ar-w59/53Bv
	w121B/187Av-w187B/195Av	w49Al-w49Bl	w51Ar-w53Av
	w187B/195Av-w195B/185Av	w25Ar-w49Av	w49Bv-w51Av
	w195B/185Av-w185Br	w25Av-s35a	w49Al-w49Bl
	w185Bv-s21	s35a	w25Ar-w49Av
	s21	w25Av-s35a	w25Av-s35a
		w25Ar-w49Av	s35a
		w49Al-w49Bl	w25Av-s35a
		w49Bv-w51Av	w25Ar-w49Av
		w51Ar-w53Av	w49Al-w49Bl
		w57A/47Bv-w53Al	w49Bv-w51Av
		s18a	w51Ar-w53Av
		s18a-w109Av	w57A/47Bv-w53Al
		w109Al-w109B/107Av	s18a
		w109B/107Av-w107B/117Av	s18a-w109Av
		w107B/117A-KW_115AR-117AL	w109Al-w109B/107Av
		KW_115AR-117AL-w117B/119A	w109B/107Av-w107B/117Av
		w117B/119Av-w125v	w107B/117A-KW_115AR-117A
		w125l-w139B/129v	KW_115AR-117AL-w117B/119A
		w139B/129v-s42a	w117B/119Av-w119B/123v
		s42a	w119B/123v-w139Av
			w139Al-s44
			s44

	4	5	6	7
From	131	132	41	42b
To	16	13	2	5
Calculated length	1615	1664	672	1067
Model output	1619,2	1674,8	692,4	1083,9
Difference (%)	-0,3	-0,6	-2,9	-1,6
Track sections	w897v-w899l	w895v-w897l	w125r-s41	s41-w791l
	w899v-w903l	w897v-w899l	w117B/119Av-w125v	s41
	w903v-w905l	w899v-w903l	KW_115AR-117AL-w117B/119A	w125r-s41
	w905v-w907v	w903v-w905l	w107B/117A-KW_115AR-117AL	w117B/119Av-w125v
	s166	w905v-w907v	s2-w107B/117Av	w113/115Av-w117B/119Av
	w905v-w907v	s166	s2	w101Bv-w113/115Av
	s21-w905r	w905v-w907v		kK_101AR-105BV-w101Br
	s21	w903v-w905l		w105Bv-kK_101AR-105BV
	w185Bv-s21	w899v-w903l		w103Al-w105Br
	w183Ar-w185Bl	s130		s5-w103Av
	w181v-w183Av	s13-s130		s5
	s16-w181r	s13		
	s16			

	8	9	10
From	45	16	13
To	2	5	2
Calculated length	727	1762	1791
Model output	740,8	1756,1	1785,6
Difference (%)	-1,9	0,3	0,3
Track sections	w127r-s45	w63r-s16	w69l-s13
	w119B/123v-w127v	w61/57Bv-w63v	w67r-w69v
	w117B/119Av-w119B/123v	w61/57Bv-w59/53Bv	w65l-w67v'
	KW_115AR-117AL-w117B/119A	w53Ar-w59/53Bv	w59/53Bv-w65v
	w107B/117A-KW_115AR-117AL	w51Ar-w53Av	w53Ar-w59/53Bv
	s2-w107B/117Av	w49Bv-w51Av	w51Ar-w53Av
	s2	w49Al-w49Bl	w49Bv-w51Av
		w25Ar-w49Av	w49Al-w49Bl
		w25Av-s35a	w25Ar-w49Av
		s35a	w25Av-s35a
		w25Av-s35a	s35a
		w25Al-w27A/25Bv	w25Av-s35a
		w27A/25B-KW_27AL-29AR	w25Al-w27A/25Bv
		KW_27AL-29AR-w31A/27B	w27A/25Bv-w29Bl
		w31A/27Ble-w31Ble	w29Bv-w33Av
		w19v-w37/31Bv	w33Al-w41A/33Bv
		w19r-w43Av	w41A/33Bv-w45v
		w43Al-s5	w45l-s2
		s5	s2