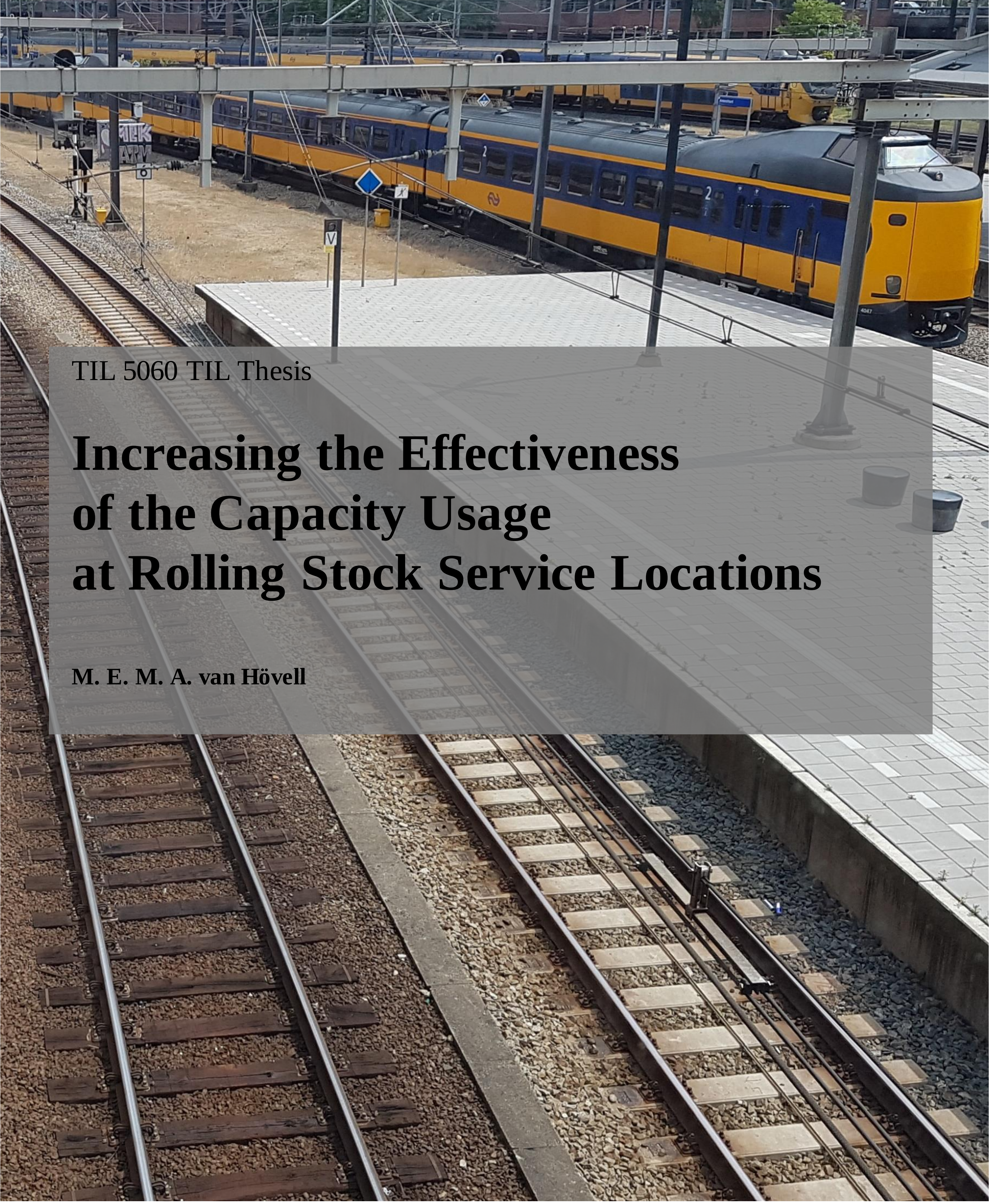

TIL 5060 TIL Thesis

Increasing the Effectiveness of the Capacity Usage at Rolling Stock Service Locations

M. E. M. A. van Hövell

Transport, Infrastructure & Logistics

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by

M. E. M. A. van Hövell

Project duration:	June 06, 2019 – December 17, 2019	
Supervisors:	Prof. dr. R. M. P. Goverde,	TU Delft
	Dr. N. Bešinović,	TU Delft
	Dr. M. M. de Weerdt,	TU Delft
	Drs. D. M. van de Velde,	TU Delft
	Ir. A. de Groot,	Arcadis

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Madeleine E. M. A. van Hövell
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Abstract

Passengers often complain about dirty trains indicating the relevance of interior cleaning of rolling stock (RS). Servicing tasks (i.e. interior and exterior cleaning and smaller technical checks) are executed on a daily basis at service locations (SLs). Currently, due to train operations during daytime, the current focus lies on night servicing. In this thesis daytime servicing is considered in order to tackle the capacity shortages at SLs. Therefore, the Rolling Stock Servicing Scheduling Problem (RS-SSP) is developed comprising a Mixed Integer Linear Programming (MILP) model. By complying with the planned timetable, the RS-SSP maximises the RS units being serviced during daytime. The RS-SSP allows RS exchanges between RS units having completed servicing and operating RS units requiring servicing. Due to this RS Exchange Concept, the number of RS units visiting the SL during daytime can be increased. Within the thesis three RS-SSP model versions have been developed: the RS-SSP Base Model and two model extensions. The RS-SSP Base Model considers trains running with a single RS unit per train and RS units to be immediately serviced when entering the SL. The first extension (RS-SSP-MU) considers multiple unit trains and the second extension (RS-SSP-MU-W) allows RS units to wait for servicing. The proposed RS-SSP models have been tested on a real-life case from the Dutch railways. The RS-SSP-MU-W yielded the most feasible and improved solutions as compared to the other two model variants. For multiple scenarios, the model was able to exchange all running RS. As a conclusion, the capacity usage at SLs can be increased by the RS-SSP by shifting the excessive workload to daytime, and thus solving the capacity shortages. As the RS-SSP model is a generic model, it may not only be applied to other railway operators, but also to other public transport companies. Further extensions on the model are suggested for an appropriate applicability on large scale.

Contents

Executive Summary

Nederlandse Spoorwegen (NS) is the Dutch railway company transporting more than one million passengers per day. In order to guarantee safety and cleanliness of the trains, rolling stock (RS) is serviced on a daily basis. Servicing comprises minor technical checks, interior and exterior cleaning, and small repairs if necessary. These servicing tasks are mostly executed at service locations (SLs) nearby a station. Currently, RS units are almost exclusively serviced during the evening and night because of operations during daytime. Currently, multiple SLs face capacity shortages during the night leading to reallocations of RS units towards other SLs. The total servicing demand does not yet exceed the total servicing capacity regarding all SLs of NS. However, NS expects a significant increase in servicing demand due to a larger number of RS units required for introducing higher train frequencies. By 2030 at the latest, the current total capacity of all SLs will be insufficient for servicing all RS units. Therefore, the goal of this master thesis was to increase the effectiveness of the capacity usage at SLs.

By trying to find a solution for more effectively using the capacity at service locations, the focus was on daytime servicing. A main counterargument of daytime servicing concerned the low availability of RS units during daytime based on train operations. For this reason, the Rolling Stock Exchange Concept was developed. It should be remarked that in multiple train series several RS units roll out towards an SL after the morning peak. Those RS units are standing at the SLs waiting for operations in the evening peak. Currently, none of these RS units are fully serviced because they represent insufficient work for employing cleaning personnel during daytime. The idea of the Rolling Stock Exchange Concept is as follows. Firstly, full servicing should be provided to those RS units rolling out towards an SL after the morning peak. Then, as soon as an RS unit completed servicing, it may substitute an operating RS unit arriving at a turning station nearby the SL. By exchanging serviced RS units with servicing requiring RS units, the number of RS units visiting the SL during daytime can be increased. This leads to a higher workload for servicing personnel making daytime servicing more efficient. Besides, more RS units can complete servicing during daytime. RS units which have completed servicing during daytime will not be serviced at night anymore. Hence, daytime servicing allows to decrease the servicing demand at night. With respect to the current servicing demand, this may solve the capacity issue of individual SLs and avoid RS reallocations. Regarding the expected increase in servicing demand, the total servicing capacity might be sufficient by introducing daytime servicing based on the RS Exchange Concept.

In order to shape the Rolling Stock Exchange Concept, a decision support model was developed, called the Rolling Stock Servicing Scheduling Problem (RS-SSP) model. The RS-SSP model presents an optimisation model or, more specifically, a mixed integer linear programming (MILP) model to be used in the tactical planning phase. Its objective is to maximise the number of RS units completing full servicing during daytime while complying with the requirements provided by the planned timetable and from the side of the SLs. The output of the model does not only indicate how many rolling stock units may complete servicing during daytime, but also provide insights into changes of the RS circulation. The resulting values of the decision variables reveal, for instance, when which RS units are exchanged at the turning station.

Goal and Scope of the Research

The purpose of this master thesis was to analyse the potential of daytime servicing with respect to the RS-SSP in order to more effectively use the capacity at service locations. As the interior cleaning of RS units entails the highest servicing frequency (i.e. once every 24 hours), it presents the most critical planning as compared to the other servicing tasks executed at SLs. Therefore, this research focuses on the interior cleaning planning. Due to time and data restrictions, the research scope was limited and based on multiple assumptions.

Firstly, service locations were considered as black boxes meaning that their precise working procedures are not taken into account. While general needs and requirements of SLs were respected as well as average servicing and shunting durations, the disparity between SLs with respect to

accessibility, servicing equipment, and walking distances were excluded from the RS-SSP model.

Furthermore, the RS-SSP relates to a network perspective rather than looking into detailed RS movements at and around a station. The reason for this is based on the model usage, referring to the rolling stock planning during the tactical planning phase. Note that testing the path accessibility of each RS movement belongs to node planning yet not to RS planning. Moreover, a wider perspective is more suitable for prospective changes (e.g. timetable changes) and less sensible for uncertainties in data accuracy.

Research Methodology

The research methodology can be split into three parts: the current state analysis, the model development, and the computational experiments. Firstly, the current state analysis consists of a literature and interview analysis specifying the needs and constraints of RS planners and SL managers. Consequently, a model framework was created comprising the findings of the current state analysis. Subsequently, the MILP model was developed. For the model application Python was used as programming language with Gurobi as solver. For the computational experiments multiple scenarios have been created based on one selected Sprinter train series. The scenarios were applied to the RS-SSP model and then evaluated. It should be mentioned that the methodology followed an iterative process. The mathematical model, the coded model, and the selection of scenarios have repeatedly been adjusted with respect to subsequent findings.

Results

Regarding the scientific relevance of this research, three main contributions can be listed. Firstly, a new mathematical model is proposed in order to more effectively use the capacity of SLs. Secondly, new possibilities of exchanging RS during daytime are submitted. And thirdly, an RS servicing frequency of once per day is considered for the first time in literature.

In total, three RS-SSP model versions have been created: the RS-SSP Base Model, the RS-SSP with Multiple Units (i.e. RS-SSP-MU), and the RS-SSP-MU with Waiting for servicing (i.e. RS-SSP-MU-W). Note that the RS-SSP-MU is an extension of the Base Model and the RS-SSP-MU-W is an extended version of the RS-SSP-MU. While the Base Model assumes that trains run with a length of one RS unit, the two model extensions allow trains to run with multiple RS units. The RS-SSP Base Model and the RS-SSP-MU assume that an RS entering the SL starts servicing immediately. The RS-SSP-MU-W, in contrast, allows RS units to wait at the SL for being serviced.

A model comparison showed that the RS-SSP Base Model features a very limited time horizon. This is based on the short time interval (i.e. off-peak hours) of trains running with a length of one RS unit. The two other models, on the contrary, have a time horizon starting with the first train arrival of a day and ending with the last train departing before the evening peak. The RS-SSP-MU-W provides the majority in feasible solutions as compared to the two other models. In case the maximum allowed number of RS units being serviced simultaneously is lower than the number of RS units rolling out towards the SL after the morning peak, the less advanced model versions yield infeasible solutions. The functionality of letting RS units wait for being serviced, however, allows the RS-SSP-MU-W to handle such limitations.

For all input parameters a critical value can be specified leading to binding constraints. Exceeding those critical values leads for several input parameters (e.g. the minimum required turning time) to an infeasible solution, whereas for other parameters (e.g. the servicing and shunting duration) the outcome is just downgraded. Relaxing the parameter values with respect to their critical values do not yield improved results yet imply buffer (e.g. buffer time for the servicing personnel). The RS-SSP appeared to be mainly sensitive on the servicing and shunting duration as well as on the maximum allowed number of RS units being serviced simultaneously. Furthermore, a combination of parameter changes enhances the impact on the model results.

The applicability of the most advanced RS-SSP model as developed in this thesis (i.e. RS-SSP-MU-W) is still limited as most train series operate multiple RS types, which are not considered by the model. Nonetheless, small extensions may improve its usability significantly. Considering RS types would be the most urgent extension, followed by multiple SLs and extending the time horizon towards one week. The strengths of the RS-SSP and challenges for the implementation have been discussed. Consequentially, supportive adaptations to be made by NS have been proposed.

One of the main challenges is the great need of clean trains in the morning. Passengers seem to be more critical with respect to hygiene and cleanliness in the morning than in the afternoon or evening. Cleaning RS units at night – as currently done – leads to clean trains in the morning, whereas cleaning at daytime may imply that RS units get dirty during afternoon and evening operations leading to more or less dirty trains in the morning. With respect to the expected increase in servicing demand, however, the current cleaning situation is definitely not in favour over the RS-SSP. The reason for this is the large number of RS units which may not meet their servicing deadline due to a lack in servicing capacity. The RS-SSP, in contrast, ensures full servicing on a daily basis due to an increase in capacity. In order to achieve higher passenger satisfaction, basic cleaning before or after each train trip may be introduced, entailing emptying bins and removing major dirt.

Another challenge refers to the unpredictability of operational disruptions leading to skipping daytime servicing appointments. This can be considered as an obstacle thwarting the planning. However, daytime servicing appointments may also be treated as buffer times for servicing. In case an RS unit cannot meet its daytime servicing appointment, its servicing is rescheduled towards the night. Naturally, this requires strong cooperation between RS controllers and SL managers.

One of the great strengths of the generic model is its applicability. Even though the experiments conducted in this thesis are focused on NS, the RS-SSP may also be applied to other railway companies as well as to other public transport operators, for instance, metro, tram, or bus networks.

Conclusions

In conclusion, the RS-SSP seems to be promising. Obviously, the RS-SSP requires further extensions in order to be used appropriately on a larger scale. The actual increase in capacity would then need to be determined. However, it becomes clear that the current servicing capacity needs to be increased and the RS-SSP provides a good solution for this sake. Expenses will, of course, be needed for implementing the RS-SSP such as additional train drivers and servicing personnel. However, all capacity increasing solutions may imply costs. It might be advisable to execute a cost-benefit analysis for implementing the RS-SSP and to compare the RS-SSP with other methods solving the lack in capacity at SLs. Further practical recommendations for NS imply a KPI alignment of RS controllers and SL managers. This may help to improve their cooperation, which is beneficial also for current planning tasks yet requisite for implementing the RS-SSP. In addition, good and timely communication with ProRail is important as the RS-SSP may lead to an increase of traffic at and around stations. The potential of the RS-SSP for Arcadis lies in further research and implementation projects at NS and other public transport operators struggling with servicing capacities.

List of Abbreviations

avg	average
BC	Behandelcalculator (i.e. servicing calculator)
BD	Basic Day
BDU	Basic Day Update
BEG	Bayerische Eisenbahngesellschaft
DB	Deutsche Bahn
DC	Dagelijkse Controle (i.e. daily cleaning)
DCR	Dagelijkse Controle Reiniging (i.e. daily control cleaning)
DCW	Dagelijkse Controle Watervullen (i.e. daily control water refill)
HIP	Hybrid Integral Planning method
inf	infeasible
MBN	Materieel Bestuur NedTrain (i.e. rolling stock management for maintenance and service)
MD-VSP	Multiple Depot Vehicle Scheduling Problem
MILP	Mixed Integer Linear Problem
MVT-VSP	Multiple Vehicle Type Vehicle Scheduling Problem
NS	Nederlandse Spoorwegen
OF	Objective Function
RS	Rolling Stock
RS-SSP	Rolling Stock Servicing Scheduling Problem
RS-SSP-MU	Rolling Stock Servicing Scheduling Problem Multiple Units
RS-SSP-MU-W	Rolling Stock Servicing Scheduling Problem Multiple Units Waiting (for being serviced)
s	second
SD	Specific Day
SD-VSP	Single Depot Vehicle Scheduling Problem
SL	Service Location
TWM	Train Washing Machine
VSP	Vehicle Scheduling Problem
VTG	Vehicle Type Groups

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1

Introduction

1.1. Introduction to Daily Rolling Stock Maintenance Planning

On an average working day, approximately 1,000,000 passengers are travelling with a train of the main Dutch rail passenger operator Nederlandse Spoorwegen (NS) (NS, 2019d). In order to provide transport for this large number of train passengers, NS currently operates a fleet of over 700 rolling stock (RS) units, consisting of over 3,000 carriages (Van Marsbergen, 2018) (see Figure 1.1). Train passengers expect trains to be functional, safe and clean. Hence, all of these trains need regular checks, repairs if necessary, as well as interior and exterior cleaning. In 2013, the Dutch daily newspaper Algemeen Dagblad wrote that train passengers complained about dirty, unhygienic and smelly trains (Van der Aa, 2013). This could recently also be read on the community web page of NS (HJS, 2018). The fact that train passengers complain about dirty trains illustrates on the one hand that clean rolling stock interiors are very important for passenger comfort and on the other hand that there might be a lack in interior cleaning.

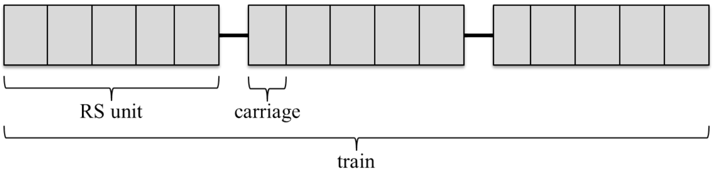


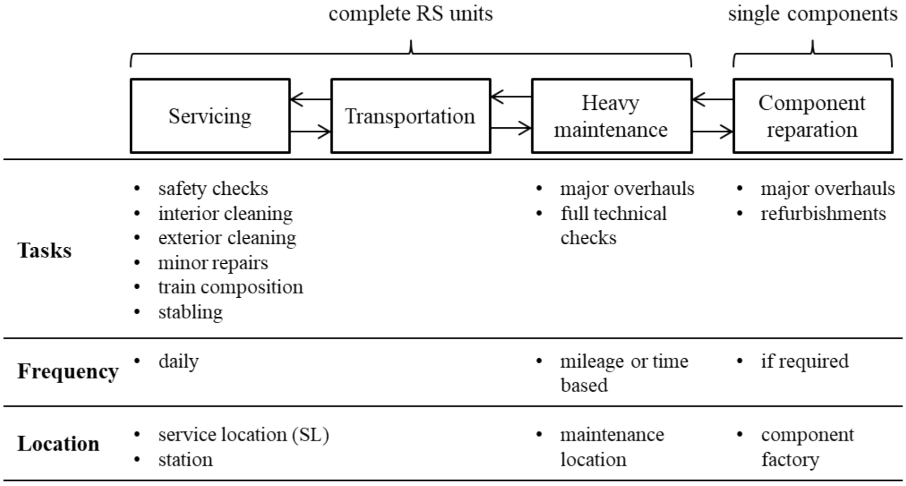
Figure 1.1: Definition of a train, an RS unit and a carriage

Since 2005, train usage in the Netherlands has increased continuously. According to the Ministry of Infrastructure and Water Management (2018) the number of passenger kilometres grew from 15.2 billion in 2005 towards 18.9 billion in 2016 representing an increase of 24%. Actually, the Dutch railway infrastructure manager ProRail expects even further large increases in train passengers. According to their expectations, the number of train passengers will grow roughly 45% from 2018 to 2030 (SpoorPro, 2018). The reasons for this trend may be explained by multiple factors, such as the increase in population, the growth of the economy, the high congestion on the road network, and the raising awareness for the environment. Both ProRail and NS react on these forecasts by planning to upgrade and modernise the rail tracks and extending the number of RS units (Treinreizigers.nl, 2018). NS plans to shorten the travel times and increase the frequency of trains as of 2020 (NS, 2019b).

As already mentioned, generating comfort and quality towards train passengers means regular checks and cleaning works for all trains in operation. These checks and cleaning works can be summarised as daily rolling stock maintenance tasks. The planned extension in RS units and higher train usage will thus even increase the demand for these daily rolling stock maintenance tasks.

Rolling Stock Maintenance

According to NS (2016), the RS maintenance logistics system at NS comprises four parts: transportation, servicing, heavy maintenance, and component reparation (see Figure 1.2). While transportation refers to train operations, the other three are maintenance related. Servicing and heavy maintenance apply to complete RS units, whereas component reparation applies to single components of an RS unit. The component reparation is performed, if necessary, at a component factory and entails tasks such as major overhauls and refurbishments. Note that the necessity of a component reparation mostly results from an inspection of the heavy maintenance. Heavy maintenance takes place at a maintenance location and involves major overhauls and full technical checks of RS units. An RS unit needs a major overhaul in case a severe problem has been detected. However, in most cases trains preventively visit the maintenance location. Depending on the RS type the deadline of the preventive maintenance check varies. The RS type *Flirt*, for instance, visits the maintenance location already after 37,000 kilometres driven or 45 days, whereas the RS type *ICM* gets its maintenance check after 77,000 kilometres or 115 days (Basten, 2013). As such major overhauls mostly take multiple days (e.g. 3 to 4 days), an RS unit needs to be totally taken out of operation during this time. Servicing comprises safety checks, interior and exterior cleaning, and, if required, small repairs. Note that there are two types of small failure checks: B- and A-check. The A-check is somewhat more intensive than the B-check and is executed every 12 days. On the day an A-check is performed, the B-check is not required anymore. Due to the diversity in tasks they vary in frequency. While the interior of each train unit should be cleaned every 24 hours, technical checks are only executed multiple times per week. Servicing tasks are executed at service locations (SLs) as well at stations. While safety inspections and interior cleaning tasks such as emptying bins do not take much time (approximately 10 to 30 minutes), they can be executed at convenient times during operations at stations (e.g. at larger dwelling or turn-around times). Daily interior cleaning at an SL, in contrast, also comprises wastewater disposal, and floor, seat and window cleaning, which are more time intensive and are thus executed at an SL. In addition to these servicing activities, trains also need to be set up in the correct train compositions at night at an SL in order to get ready for the next day. As most trains are in operation during daytime, the servicing tasks are mostly performed during the night shift (i.e. 11pm to 7am) (Basten, 2013). At NS, the responsibility of the rolling stock maintenance is assigned to the departments Service, Maintenance, and Modernisation; previously this was NedTrain (NS, 2019c). Figure 1.2 provides an overview about the frequencies and tasks associated with the different maintenance types.



Tasks	• safety checks • interior cleaning • exterior cleaning • minor repairs • train composition • stabling	• major overhauls • full technical checks	• major overhauls • refurbishments
Frequency	• daily	• mileage or time based	• if required
Location	• service location (SL) • station	• maintenance location	• component factory

Figure 1.2: RS maintenance logistics system at NS based on NS (2016)

Capacity Issues at NS Service Locations

In total, NS owns 30 service locations, which are spread over the Netherlands (NS, 2019a). Figure 1.3 illustrates the distribution of the service locations.

Figure 1.3: Service locations operated by NS (Janssens, 2017)

Currently, the service locations already face capacity issues during the night shift. According to Ten Broek (2019) and to Schemmekes & Van Heusden (2019) the physical capacity (i.e. stabling capacity) and the service capacity (i.e. number of technical and cleaning staff) represent the main bottlenecks at service locations. There are differences in sizes and capacity volumes between service locations. In general, the service locations in the Randstad (i.e. Amsterdam, The Hague, Utrecht) are busier than those outside of the Randstad. As for several service locations the service capacity is lower than the demand (Grunbauer, 2019), RS service tasks need to be assigned to other SLs, which have remaining capacity. However, not all service tasks can be executed at all service locations. Exterior cleaning, for instance, can only be performed at service locations with a wash installation. The growth in train usage and the increasing number of trains operating on the Dutch railways will lead to an even higher service demand, and hence increases the lack in physical and service capacity even further. Therefore, NS already started investigations to solve this capacity issue. Moreover, also the design, engineering and management consulting company Arcadis wanted to proactively assess possible solutions for NS.

1.2. Problem Formulation

As the volume of rolling stock will increase in the near future, the request for extending the service locations rises. However, such service locations require large surface areas and imply environmental disturbances, such as noise and light. Besides, it becomes more and more difficult to find personnel for the daily rolling stock maintenance as it is mostly night work. Hence, the extension of a service location or the construction of a new one faces spatial, economic, and social problems (Ten Broek, 2019).

In order to tackle the lack in service capacity at service locations, NS already started investigating alternative solutions. The most promising solution approach strives to increase the usage rate of the service locations by means of processing rolling stock units also during daytime. However, there are two main issues when trying to plan rolling stock maintenance tasks during daytime (B. Huisman & Zomer, 2019). Firstly, there is a lack in supply of rolling stock units, meaning that with respect to the timetable most RS units have no time to be serviced during daytime. Secondly, as the interior of each rolling stock unit has to be cleaned every 24 hours, it means that a rolling stock unit which is once cleaned during daytime should always be cleaned during daytime. This represents a huge logistical challenge as the specific rolling stock units circulate through the Dutch network and do not pass the same service locations every day during daytime. Therefore, the chance is very small that a rolling stock unit, which would be cleaned at a certain service location today during daytime, will be at that same service location on the following day during daytime. This means that multiple service locations would need to be analysed for availability in order to guarantee that an RS unit is cleaned every 24 hours. Here, the question arises whether a rolling stock unit that stops every day during daytime at a station with a suitable service location will have enough time to be serviced. Apparently, in the current situation this question is impossible to answer as the rolling stock circulation is often being adjusted during operations (B. Huisman & Zomer, 2019). Even though the rolling stock circulation is planned in advance, rolling stock units with a technical defect featuring safety risks need to be taken out of the RS circulation. Those types of operational adjustments are not known in advance and can thus not be planned. Certainly, a strict plan could determine that each rolling stock unit has the same circulation every day and stands at the same moment during daytime at the same service location. However, this would restrict the planning to a large extent, making such a planning undesirable.

As the predictability of the rolling stock circulation is not precise enough, it might be possible to solve the two presented issues by means of increasing the number of rolling stock units visiting a service location where they can be cleaned during daytime. This could be ensured by regularly exchanging operating rolling stock units at nodes with a service location that has rolling stock units of the same type in reserve (B. Huisman & Zomer, 2019).

A decision support model is necessary to actually determine which rolling stock units should be exchanged at which service location at which moment during daytime. Hereby, the aim is to service as many rolling stock units as possible during daytime with respect to their 24hour cleaning deadline. Undoubtedly, the rolling stock circulation needs to be adapted by exchanging rolling stock units, yet the timetable for passengers is seen as nonadjustable. In the framework of this research study, the logistical challenge of reassigning rolling stock units to service locations during daytime is addressed at a tactical level. The presented problem is called the Rolling Stock Servicing Scheduling Problem (RS-SSP).

1.3. Research Question

This master thesis aims to improve the situation at service locations with respect to their capacity issues at night. Therefore, the following research question is defined:

How to use the capacity at service locations more effectively?

To answer the main research question, a set of subquestions is defined:

1. Which requirements and restrictions play an important role for daytime servicing?
2. Could a rolling stock exchange support daytime servicing?
3. What information, knowledge and data is required for a decision support model?
4. Which functions should a decision support model feature in order to improve the capacity usage at service locations?
5. What adaptations at NS may support the applicability of the RS-SSP?
6. How does the RS-SSP impact different stakeholders?

1.4. Scope of the Research

This research focuses on the servicing planning at NS. More precisely, the focus lies on the cleaning of the RS interior, which is executed every 24 hours and thus presents the highest frequency and the most critical daytime planning of all daily rolling stock maintenance tasks executed at service locations. Through a decision support model that determines which rolling stock units should be exchanged at which service location for daytime servicing, the usage of service locations could be increased. The RS-SSP model is developed and then applied to the Dutch railway network. However, due to time and data restrictions, the scope was restricted and multiple assumptions were made.

Service locations were not analysed into detail. Actually, they were seen as black boxes and only a few constraints from the point of view of the service locations were considered in the optimisation model (e.g. maximum number of RS units possible to service simultaneously at an SL). Several average values were used as general assumptions, such as the average servicing and shunting duration.

The optimisation model which was established within the framework of this study and subsequently applied to the railway network represents a network perspective and does not look into detailed train movements and shunting at a station. This was a deliberate decision as a model with a network perspective is less dependent on accurate data. The data provided by NS is the planned rolling stock plan and not historical data. The reason for this is based on the usage of the model in the planning phase, where no more than the planned data is available. Nevertheless, the planned data may deviate from the realised data. With respect to the future, the rolling stock plan may be different due to timetable changes. For a model with a wider perspective, this uncertainty of data accuracy is less grave than for a model specialised on a single station comprising all details of this station.

1.5. Research Structure

The research methodology is split into three parts as visualised in Figure 1.4.

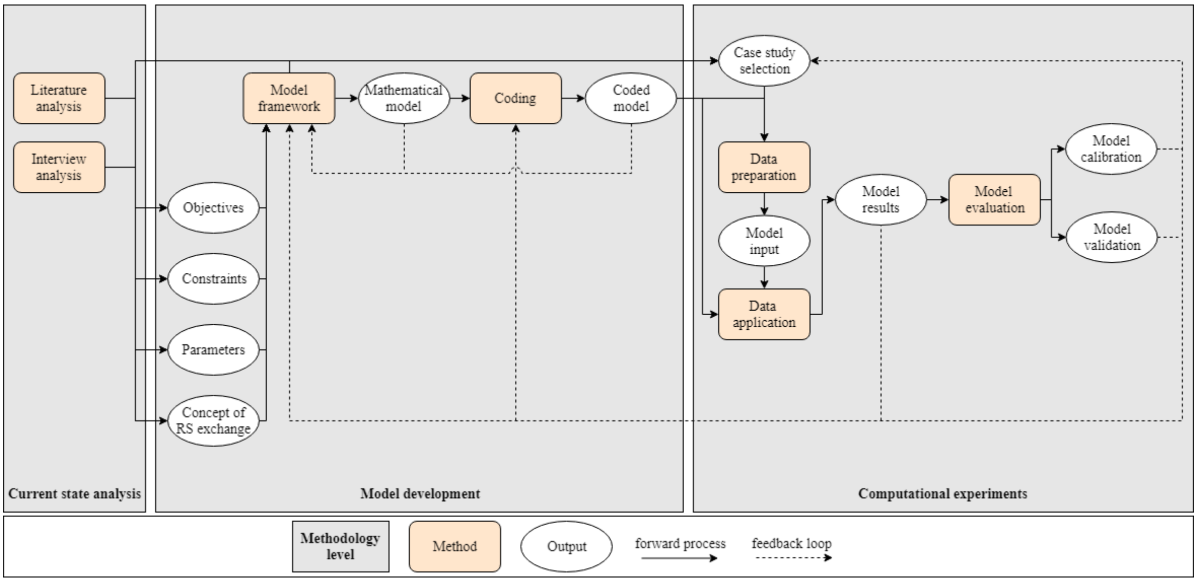


Figure 1.4: Conceptual methodology

The three parts can be described as the current state analysis, the model development, and the computational experiments. Within the current state analysis qualitative analysis was done consisting of literature research and interviews. The current situation and planning were assessed including the needs and requirements with respect to the rolling stock exchange concept. Next, based on all analyses, the model framework was developed, and the model code was written. In the last phase, the model was tested on multiple scenarios. By means of calibration and validation techniques, the model was evaluated with respect to its functionality and validity. In order to assess the quality of the results, a comparison with existing solutions has been executed.

As can be seen, there are multiple feedback loops indicating the iterative development of the model. The process from the framework until the model evaluation was not direct, but often led to a modification of a previous output.

The outline of this thesis follows the structure of the methodology. The current state analysis is divided into a literature review in Chapter 2 and an assessment of the current rolling stock and service planning in Chapter 3, which is based on literature analysis and interviews. Then, Chapter 4 presents the Rolling Stock Servicing Scheduling Problem including the developed model. The computational experiments are described in Chapter 5. Here, the selected scenarios are defined, the model results are shown, and the model is evaluated. In Chapter 6 the usability of the model is discussed with respect to the current situation as well as its adaptability for changes. The conclusions can be found in Chapter 7 including recommendations for further research and practical recommendations to NS.

2

Literature Review

This Chapter provides a literature review in order to obtain an overview of topics already investigated regarding the Rolling Stock Servicing Scheduling Problem. First, Vehicle Scheduling Problems (VSPs) are reviewed in Section 2.1. VSPs have similarities with the RS-SSP as they encounter similar problems, where vehicles need to be assigned to trips and depots. However, VSPs are mostly applied to busses and do not consider all constraints necessary for the railway planning. Hence, Section 2.2 presents models regarding rolling stock planning. In Section 2.3, maintenance routing models are reviewed and finally the scientific relevance of this master thesis is explained in Section 2.4.

2.1. Vehicle Scheduling Problems

Over the last 40 years, the Vehicle Scheduling Problem has already been studied extensively. Vehicle scheduling refers to the assignment of vehicles to trips planned in a timetable. Often studies of VSPs are related to transportation or decision support systems in general (e.g. Bodin & Golden (1981) and Bodin et al. (1983)), others also specialise on a solution approach, such as Daduna & Paixão (1995) or Mesquita & Paixão (1999). As the vehicle scheduling problem is a typical problem arising in public transport bus companies, most approaches regarding VSPs focus on the assignment of busses. Bunte & Kliewer (2009) give an overview of approaches for problem extensions for the VSP. Here, differences can be made between, for instance, one or multiple depots, and one or multiple vehicle types.

Single Depot Vehicle Scheduling Problem

The simplest case of the vehicle scheduling problem is the single depot problem (SD-VSP). The SD-VSP was first optimally solved by Saha (1970). Saha reformulated the problem as a network flow problem and solved it as a Minimal Decomposition Model. The operational costs were not taken into account nor was it possible to set an upper bound for the fleet size. Orloff (1976) formulated the assignment model, which can handle both drawbacks of the Minimal Decomposition Model. Later, Gavish & Shlifer (1979) developed the Transportation Model, which may also be modelled according to a bipartite graph structure. Daduna & Paixão (1995) extended this model for the case of infeasibility by introducing arcs with penalty costs between all trip nodes. Due to this extension a vehicle schedule can be obtained even though not all trips are served. Bodin et al. (1983) presented a network flow approach, which was later obtained by Bertossi et al. (1987) due to reformulation of a capacitated matching problem. It is proven that this problem can be solved in polynomial time. In literature multiple constraints have been taken into account with respect to the single-depot case and Freling et al. (2003), for instance, also integrated vehicle and crew scheduling.

Multiple Depot Vehicle Scheduling Problem

The multiple depot case of the vehicle scheduling problem (MD-VSP) is an extension of the SD-VSP, whereby multiple locations, i.e. the depots, are considered for starting bus routes. Here, a constraint is added by forcing vehicles to return to their starting depots at the end of their route.

As one of the first, Hoffstadt (1981) used the assignment model for dealing with the multiple depot case. A few years later Bertossi et al. (1987) proved that the MD-VSP was NP-hard.

Carpaneto et al. (1989) solved the MD-VSP for the first time in an exact way. They assigned freight vehicles to different depots and used a branch and bound algorithm for the optimal solution. They presented a connection based network structure, where on the one side each available vehicle per depot represents a node and on the other side each trip represents a node. Each vehicle node is connected by an arc with each trip node and the other way around. The two different types of nodes are connected by arcs. By means of additional arcs pointing towards the same node and fixed costs per arc, the usage of unnecessary vehicles can be avoided. Fischetti et al. (2001) used a branch-and-cut algorithm, where paths could be eliminated. Unfortunately, the number of constraints grows exponentially in this model, which has a negative impact on the computation time.

Kliewer et al. (2006) shows how to construct a Time Space Network (TSN), which aggregates connections between groups of compatible trips. Therefore, the TSN features a highly reduced number of arcs compared with a connection based network structure without losing any feasible vehicle schedule. Furthermore, Kliewer et al. (2006) uses a Mixed Integer Programming (MIP) optimisation in order to solve the MD-VSP. Very large-scale instances of MD-VSP could be solved by a two-phase heuristic approach (Gintner et al., 2005). Thus, several connections are fixed before solving the MD-VSP. Steinzen et al. (2010) used the time-space network representation for the integrated vehicle- and crew-scheduling problem and according to Berthold et al. (2019) this integration already works well in practice.

Vehicle Scheduling Problem with Multiple Vehicle Types

In most of the previous described VSPs, it is assumed that the fleet is homogeneous, meaning that there is only one vehicle type. Lenstra & Kan (1981) showed a vehicle scheduling problem with multiple vehicle types (MVT-VSP). They proved that the MVT-VSP is NP-hard already without multiple depots.

In literature, there is already a large number of heuristic and exact optimisation approaches regarding MVT-VSPs (e.g. Lenstra & Kan (1981), Smith & Wren (1981)). Mostly MVT-VSPs are based on a multigraph having a subnetwork for each combination of depot and vehicle type. Bodin et al. (1983) and Costa et al. (1995), for instance, used this approach for the single depot case (SD-MVT-VSP). In case the scheduled trips can only be serviced by a subset of vehicle types, an extension is added, i.e. vehicle type groups (VTG). The multiple depot case with vehicle type groups (MD-VTG-VSP) is also considered by Kliewer et al. (2006).

According to Bunte & Kliewer (2009), further research is required in order to integrate vehicle scheduling with other planning tasks (e.g. maintenance planning tasks). Furthermore, the VSP is mostly applied to busses. Therefore, it misses several constraints with respect to railway problems. Trains may consist, for instance, of multiple RS units, which can be (de-)coupled during operation. Busses, on the contrary, normally operate as single units.

2.2. Rolling Stock Planning

In railway planning there are multiple subtasks, such as network planning, line planning, timetable generation, vehicle scheduling, crew scheduling and crew rostering. Although, these subtasks directly depend on each other, their focus lies on different questions. The need for dividing the railway planning into multiple subtasks is partially based on the high complexity of the overall planning process (Liebchen & Möhring, 2007). Bussieck et al. (1997) and Maróti (2006) provide explanations and solution approaches to each of the above mentioned planning steps. In the framework of this master thesis, the focus is on vehicle scheduling, also called rolling stock planning. A large number of studies consider rolling stock planning for the case of railway traffic (e.g. Maróti (2006), Peeters & Kroon (2008), Borndörfer et al. (2011), Haahr et al. (2016), Berthold et al. (2019)). Actually, there are three different RS planning tasks, namely the RS allocation (i.e. allocating the number of RS units and the RS types to each train series), the RS circulation (i.e. allocating RS units to each trip), and the RS allocation with respect to the specific RS units. In practice, the latter is done manually on the day of operation. Also, in literature no optimisation approach exists for allocating the specific RS units to the vehicle circulation. Hence, the next two paragraphs outline the former two RS planning tasks.

Rolling Stock Allocation

The allocation of RS types towards train series and determination of the number of RS units can be summarised as RS Allocation. The RS Allocation represents the first step in the planning process of the rolling stock. According to D. Huisman et al. (2005) this is usually done for a standard day of the week (e.g. for a Tuesday). The objective of the RS Allocation is to match the required and the provided capacity of trains. A lack in train capacity might hinder all passengers being accommodated, whereas overcapacity is costly and may lead to a lack in capacity on another train series. Also, preferences, such as more comfortable trains for long-distance traffic, and constraints, such as maximum train lengths with respect to the platform lengths, influence the RS Allocation. In order to optimise the train allocation for different train types, Abbink et al. (2004) developed an MIP model. Their model minimises seat shortages on the trains in the morning peak. The model was applied to a case study of NS and showed fast solutions by means of the solver CPLEX.

Rolling Stock Circulation

After the type and number of RS units have been allocated to each train series, the rolling stock circulation problem addresses the appropriate assignment of RS units to the scheduled trips. This implies the routing of each RS unit. Consequently, accommodation of all passengers, efficiency and robustness are important objectives (see Alfieri et al. (2006), Peeters & Kroon (2008) and Borndörfer et al. (2017)). Usually, the RS circulation is planned for a basic week. In a first step, the RS circulation is planned for each day of the week separately and in a second step the RS circulation is balanced over the week. The second step ensures that the number and types of out-going RS units at a node in the beginning of an operational day matches with the number and types of in-going RS units at that same node at the end of the previous day.

Also, the order of the train units in the trains needs to be taken into account when planning the RS circulation as several train units can only be coupled to the rear position of a train. As this problem cannot be solved with the multi-commodity flow model, Alfieri et al. (2006) and Peeters & Kroon (2008) developed the concept of a transition graph. In the transition graph, it is possible that train compositions change within the journey. Alfieri et al. (2006) solved this problem in a relatively short time by CPLEX. However, the Branch-and-Price approach used for instance by Peeters & Kroon (2008) normally outperforms CPLEX with respect to the running time. While the transition graph assumes that composition changes can only be executed at turning points of a train series, Fioole et al. (2006) extended the transition graph in order to allow trains to couple or decouple along the way. This extended model is called the Composition model. According to Wagenaar & Kroon (2015), NS has been using the Composition model for RS scheduling since 2004.

Also, Borndörfer et al. (2011) studied the optimisation of the RS circulation problem. They proposed a hypergraph model and solved it by means of Integer Programming techniques. These were applied to large-scale real world instances of DB Long-Distance Traffic. It considered a cyclic planning horizon over one standard week. The model has the objective to minimise the vehicle cost, deadhead cost, coupling cost, and irregularities, thus covering constraints that ensure that each trip is assigned to a node and each vehicle to a trip. Furthermore, in-flow and out-flow constraints need to be met to comply with the flow conservation of each node. However, maintenance costs or other maintenance related constraints have not been taken into consideration.

2.3. Maintenance Routing

As rolling stock is a valuable and costly asset of railway operators, they need to be well maintained. This means that they regularly need to be cleaned, checked, and repaired if necessary. These tasks are executed at maintenance and service facilities (D. Huisman et al., 2005).

Due to the complexity and stochastic nature of maintenance, maintenance planning is in practice often executed manually. This is a time-consuming process and leads to non-efficient solutions (Lai et al., 2015). In the past, models have been established with respect to maintenance planning. An example from the aerospace context is the research of Feo & Bard (1989). This study tries to integrate maintenance routing within the flight schedule by minimising costs including maintenance costs. Within the railway sector, the focus on maintenance planning has started later. Sriskandarajah et al. (1998) developed an optimisation model for scheduling large RS maintenance tasks, which incorporated several maintenance planning constraints. Penicka & Bjørner (2004) presented a model solving the RS maintenance routing problem. However, maintenance constraints have not been taken into account for the scheduling problem. Then, Maróti & Kroon (2005) described a transition model for routing trains towards maintenance facilities. For this model, the regular timetable plan and a list of urgent rolling stock units with a maintenance deadline are used as input. The regular plan partly requires adjustment in order to route urgent rolling stock units to a maintenance facility while carrying out timetable services. Two years later, the same authors (Maróti & Kroon, 2007) present an integer programming model ensuring that urgent rolling stock units reach the maintenance facility in time. The objective of their algorithm is to find the minimal cost flow in the constructed network. Also, Borndörfer et al. (2011) proposed a model for the RS circulation planning taken the cleaning and maintenance time into account. Moreover, Tönissen & Arts (2018) solved an NP-hard maintenance location routing problem by considering the possibility of opening additional facilities, closing facilities, and increasing the facility capacities. They developed a MILP model, which aims to minimise the total annual facility costs. The model allows interchanges between RS units, yet only large maintenance works with an occurrence of once every half year up to every month are taken into account.

According to Giacco et al. (2014), the coordination of maintenance and rolling stock scheduling is still under-investigated. They highlighted the importance of covering services and maintenance tasks within the RS circulation planning with a limited number of rolling stock units. For this problem they developed a model with a two-step approach combining scheduling tasks with respect to train services, short-term maintenance works, and empty runs. Eventually, they applied their model to case studies of the Italian railway company Trenitalia and achieved improvements regarding cost reductions. A year later, Lai et al. (2015) developed a model to improve the efficiency in rolling stock usage by optimising the rolling stock assignment and maintenance plan for daily and monthly inspections on operational level. Also, Andrés et al. (2015) defined a detailed maintenance routing model to deal with rapid transit network problems. Therefore, an efficient Bellman-Ford's multilevel algorithm was used for each train type. Both models have taken multiple regulations into account such as train scheduling and maintenance constraints and focus on daily and monthly inspections.

Note that there are also multiple papers in literature addressing the Rolling Stock Rescheduling Problem (RSRP) (e.g. Wagenaar & Kroon (2015)). The RSRP tries to maintain a feasible rolling stock circulation after a disruption has occurred. As a consequence, trains need to be rescheduled. The RSRP differentiate from scheduling problems especially with respect to calculation time requirements. While rescheduling problems need to be solved near real-time and thus require fast calculation times, scheduling problems have less time pressure. Wagenaar & Kroon (2015), for instance, developed three RSRP models based on the Composition model of Fioole et al. (2006), whereas scheduled maintenance appointments are taken into account. In the first model additional rolling stock types are added for RS units requiring maintenance. The second model puts maintenance constraints on maintenance requiring RS units. The third and fastest model creates paths for every rolling stock unit ensuring that RS units requiring maintenance reach a maintenance facility in time. All RSRP models of Wagenaar & Kroon (2015) consider maintenance routing for RS units, which require maintenance at a specific moment in time. This is similar to the maintenance routing models described before. The RS-SSP, however, is more flexible in time and aims to maximise the number of RS units visiting a service location rather than privileging urgent RS units.

Giacco et al. (2014) pointed out that further research is required with respect to limiting the workload for the maintenance operators. Moreover, none of the models consider the efficient usage of the maintenance facilities. Furthermore, the above described models do not incorporate daily RS servicing such as interior cleaning deadlines.

2.4. Scientific Relevance

A general problem is that train operators create the timetable without considering daily rolling stock maintenance. Due to an economic point of view, the timetable is planned such that the train usage is maximised. Hence, the dwell times at end stations are relatively short. In literature the maintenance routing models mostly use the timetable as input, which is difficult to adjust. In several models timetable adjustments are allowed, yet only for urgent cases (i.e. maintenance deadlines). Urgent cases imply safety checks, which can be scheduled every two or three days. However, each rolling stock unit should be cleaned daily, which is not considered in any model. When RS units need to be routed every day to a service location, individual deadlines do not need to be considered anymore. This is especially the case, when the moment in time does not play an important role. Hence, the main difference of routing each RS unit every 24 hours to a service location, as opposed to maintenance deadlines of 2 or more days, is the insignificance of individual deadlines.

Therefore, this master thesis aims to find an intelligent way of increasing the usage of service locations by maximising daily rolling stock maintenance performances during daytime. Exchanging operating rolling stock units with serviced rolling stock units being in stock at service locations may increase the number of rolling stock units serviced during daytime. Simultaneously, such an exchange might not violate the timetable planning.

Vehicle Scheduling Problems laid the foundation for RS scheduling problems in the sense that vehicles need to be assigned to scheduled trips. As trains may consist of multiple RS units and are restricted to certain train compositions, additional aspects need to be taken into account. Coupling and decoupling do, for instance, play an important role in the railway context as well as RS unit interchanges. Therefore, the following paragraph focuses on railway related studies.

In Table 2.1 an overview of the studies regarding RS planning is given, distinguishing the incorporated aspects (see columns). Also, the model developed in this thesis (i.e. the RS-SSP model) is included in this overview.

	RS related			maintenance related				
	RS allocation	RS circulation	RS interchanges	maint. costs	large maint. works	short-term plan.	daily inspections	daytime cleaning
D. Huisman et al. (2005)	x							
Abbink et al. (2004)	x							
Alfieri et al. (2006)		x	x					
Peeters & Kroon (2008)		x	x					
Fioole et al. (2006)		x	x					
Haahr et al. (2016)		x	x					
Sriskandarajah et al. (1998)	x				x			
Penicka & Bjørner (2004)		x		x	x			
Maróti & Kroon (2005)		x	x	x	x			
Maróti & Kroon (2007)		x	x	x	x			
Borndörfer et al. (2011)		x	x	x	x			
Tönissen & Arts (2018)		x	x	x	x			
Berthold et al. (2019)		x	x		x			
Giacco et al. (2014)		x	x	x	x	x		
Wagenaar & Kroon (2015)		x		x	x	x		
Lai et al. (2015)		x	x	x			x	
Andrés et al. (2015)		x	x	x			x	
RS-SSP model		x	x				x	x

Table 2.1: Literature overview regarding RS planning

In literature only a few papers allow changes in the RS circulation plan in order to route urgent RS units to a maintenance facility (see Table 2.1 “RS interchanges”). In Maróti & Kroon (2005) and Maróti & Kroon (2007), for instance, it is possible to interchange tasks of urgent RS units with non-urgent RS units. However, RS exchanges as proposed in this thesis have not been considered in any study before according to the best of the author’s knowledge. Furthermore, there are only a limited number of studies considering smaller technical checks with frequencies of approximately 3 times per week. Moreover, none of the existing models take interior cleaning for RS into account, which needs to be executed every 24 hours. This is logical as currently this task is usually performed at night. This type of maintenance routing is, thus, in current RS circulation plans automatically integrated in the evening route plan towards the stabling yard. The model developed in this paper is the first that considers daytime servicing with a 24 hour meantime between cleaning.

Hence, in the framework of this master thesis a decision support model was developed for the Rolling Stock Servicing Scheduling Problem determining which rolling stock units should be exchanged at which time.

The main contribution of this research is threefold.

- A new mathematical model RS-SSP is proposed in order to more effectively use the capacity of service locations
- New possibilities of exchanging rolling stock during daytime are proposed
- For the first time an RS service frequency of once per day is considered

3

Current Rolling Stock and Service Planning

The following chapter addresses the first two subquestions – *"Which requirements and restrictions play an important role for daytime servicing?"* and *"Could a rolling stock exchange support daytime servicing?"*. It is based on literature analysis and interviews with NS employees and experts in the field of railway planning and operations. Firstly, the planning process of NS for creating the timetable, rolling stock plan, and node plan is described in Section 3.1. Then the service planning is analysed into more detail in Section 3.2. In Section 3.3 the coordination between the RS planning and the service locations is analysed and in Section 3.4 the service planning system of NS is compared to Deutsche Bahn (DB) Regional. Finally, the concept of exchanging rolling stock units is outlined in Section 3.5.

3.1. General Planning Process

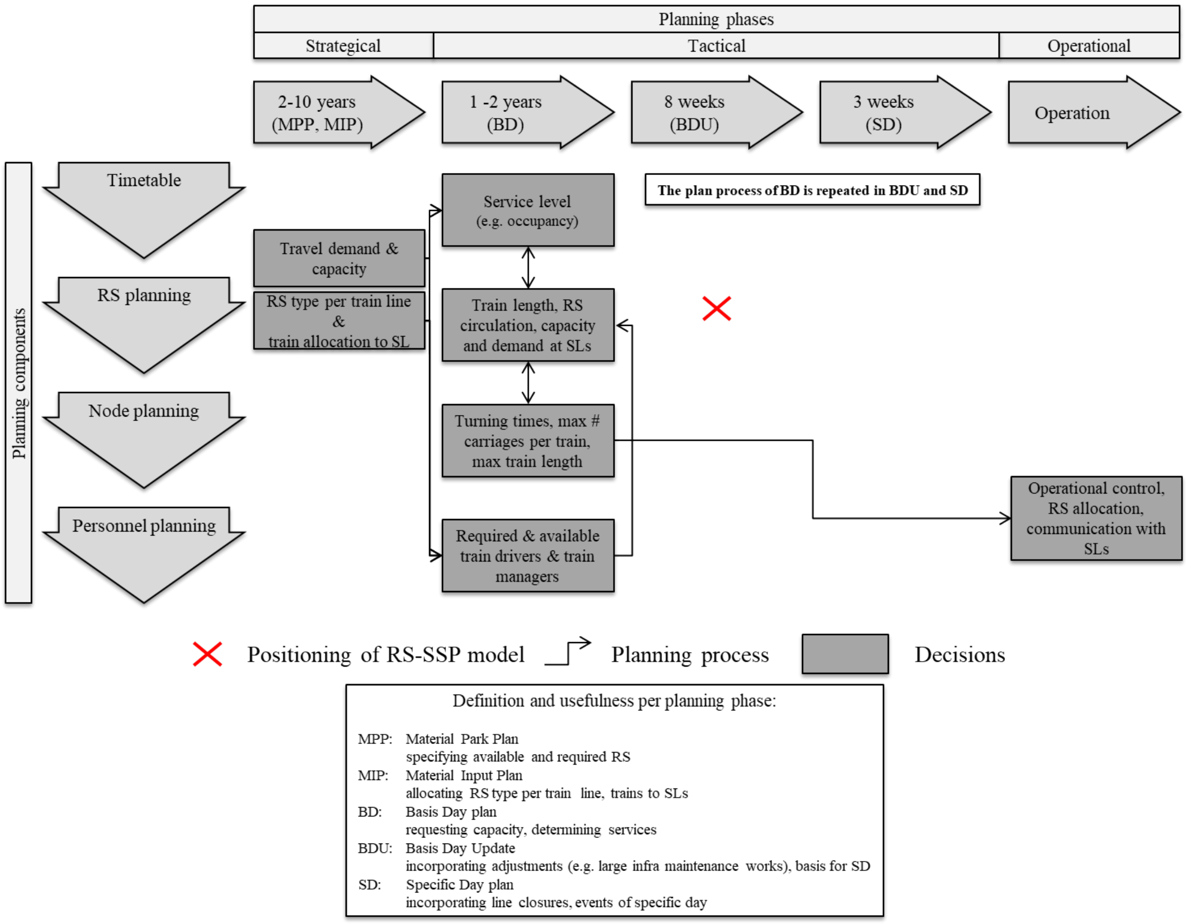
The planning process can be divided into four planning components and three planning phases as visualised in Figure 3.1 (Fleuren, 2019). The planning components consist of the timetable, the rolling stock (RS) planning, the node planning, and the personnel planning. The planning phases refer to the strategical, tactical, and operational planning phase, which occur in different periods of time.

Planning Components

Firstly, the timetable is planned to indicate the departure and arrival time of trains at train stations. All stations need to be connected. The passenger demand is taken into account for determining the frequency. Actually, all indications important to the passenger are given in the timetable, such as departure and arrival times, dwelling times, and frequencies. The timetable is used as the basis for the rolling stock plan. The objective of the rolling stock plan is to use the available rolling stock as efficiently as possible in order to meet passenger demand. Hence, the train lengths including the rolling stock type and the number of rail carriages are determined according to the required train capacity. As one rolling stock unit may consist of multiple carriages, the length of a train can be indicated more precisely by the number of carriages than by the number of rolling stock units.

The rolling stock plan also adapts the platform at which a train shall arrive and depart. It is specified in the timetable in case the previous selected platform does not provide sufficient capacity for the length of the train. Furthermore, the rolling stock plan represents the complete rolling stock circulation including the servicing and maintenance routing. According to Fleuren (2019), the rolling stock planning contains two parts – the rolling stock allocation based on the timetable and on the network balance. The former allocates the rolling stock such that the timetable can be applied, whereas the latter regulates the balance between the number of trains arriving and departing at service locations. Moreover, the circulation of the train drivers and the crew needs to be planned, which may sometimes lead to additional train movements outside of the timetable. Naturally, the timetable and the network balancing based RS planning have large impacts on each other.

While the timetable and the rolling stock plan concern the entire (Dutch) rail network, the node planning explores the rolling stock movements within a node. Note that a node may consist not only



Definition and usefulness per planning phase:

MPP: Material Park Plan
specifying available and required RS
MIP: Material Input Plan
allocating RS type per train line, trains to SLs
BD: Basis Day plan
requesting capacity, determining services
BDU: Basis Day Update
incorporating adjustments (e.g. large infra maintenance works), basis for SD
SD: Specific Day plan
incorporating line closures, events of specific day

Figure 3.1: Current planning process of NS

of a station, but also of one or multiple adjacent service locations (see Figure 3.2). A node plan is, thus, a plan for the entire (i.e. integral) node from the moment that the passengers embark at a station until the train is ready for boarding. Hence, a node plan entails when and via which paths rolling stock units drive towards a service location, how they shunt within a service location, where they are stabled, when, where and by whom they are serviced, and in which train each rolling stock unit departs.

On behalf of the node plan, the rolling stock plan is checked for feasibility for the nodes, and if necessary adjusted. The feasibility of the rolling stock plan regarding its own scope (i.e. the network and some local norms for the node planning) is checked while making the initial rolling stock plan. However, the interactions between the rolling stock plan and the node plan are very complicated due to the large numbers of restrictions with respect to shunting, path accessibility, and capacity issues at SL. Therefore, an integral feasibility check for the node is required when the rolling stock plan is completed. This node plan can be generated by a generic tool called *“Hybrid Integral Planning method”* (HIP). HIP is a module of the *“Behandelcalculator”* (BC), which consists also of a database, an instance generator, and an analysing tool determining whether a plan works or not. The BC may support all planning phases of the node planning as will be explained in the next paragraph. All NS service locations are incorporated in the BC. However, currently the node plan is made manually as the BC is not used for the planning yet.

Even though the personnel planning, i.e. train driver and train manager, plays an important planning component, it is less relevant for this research and thus not further analysed.

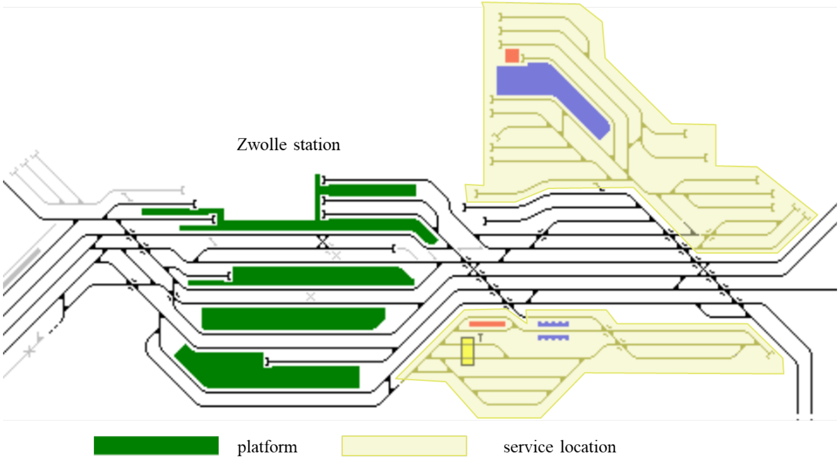


Figure 3.2: Visualisation of the node Zwolle consisting of a station and a service location (Sporenplan.nl, 2019)

Planning Phases

Per planning phase, NS develops several plan products as indicated in brackets (i.e. MPP, MIP, BD, BDU, and SD) in Figure 3.1. The content related outcomes of the plan products are described in the dark boxes in line with the corresponding planning component. The *"Materieel Park Plan"* (MPP) and *"Materieel Inzet Plan"* (MIP) are, for instance, two long-term plan products (i.e. 2 to 10 years in advance). While the MPP comprises all available rolling stock of NS and specifies which rolling stock is required, the MIP contains information about the rolling stock type per train series and allocates the trains to service locations.

Within the tactical planning phase there are three planning products, namely the *"Basic Day"* (BD) plan, the *"Basic Day Update"* (BDU) and the *"Specific Day"* (SD) plan. The BD plan presents a generic week for an entire year and is used to request the required paths from the infrastructure manager (i.e. ProRail). The BDU represents an update of the BD plan which also comprises one week yet is customised to approximately 8 weeks. Finally, the SD plan is created 3 weeks before operation, which applies to one specific day (Schemmekes & Van Heusden, 2019). The BDU and SD plan are customised with respect to, for example, demand fluctuations and track maintenance. All these updated plans are finally sent to the infrastructure manager for path requests.

In the operational planning phase, the SD plan is executed as well as possible; in case of a disruption, local rolling stock controllers need to find a solution that minimises the deviation from the plan and subsequently restore the plan. This requires flexibility of the node plan because it may entail RS units to be taken out of or inserted into the network. Another need for flexibility of the node plan is the uncertainty of servicing tasks to be performed – since the rolling stock plan may change during the day (due to small or large disturbances) it is uncertain which RS units end at which service locations. Hence, the servicing needs will remain uncertain (Fleuren, 2019, Schemmekes & Van Heusden, 2019).

Note that each plan features the same level of detail as they are all planned to an exactness of six seconds. This is typical for the railway planning, yet very different to, for instance, the production planning of a factory. There is more uncertainty in the long-term plans than in the short-term plans. For this reason, a factory would only set up a rough plan for the strategic planning and go more into detail when the delivery date comes closer. However, the railway planning is so complex that a rough plan would not give sufficient insight for determining the required capacity. Such a detailed planning costs many hours of work (Schemmekes & Van Heusden, 2019). Obviously, tools are used in order to facilitate the planning, yet they vary in functionality. For the timetable planning, there is a central system called *'Donna'*, which is used from circa 2 years in advance until the day before the day of operation. For the long-term planning (i.e. 2 to 10 years in advance) the system *'DONS'* is used. The RS plan is created by means of an optimisation model called *'Tool voor Aanpassing Materieelinzet'* (TAM) (*English: Tool to adjust the rolling stock assignment*). The node plan is currently mainly created manually with aid of a visualisation tool. Only at one node an optimisation model called *'Opstelplan Generator'* (OPG) is partly used, which generates the most efficient routes from platform tracks to parking tracks and determines departure times of the trains. For most of the nodes, the OPG did not give sufficient support. In the future HIP may be used as described above. Maybe HIP and OPG will be integrated at a certain moment because the functionality of the two models is very similar (in fact, only their solving method is different). The network based personnel planning uses a software package *'Cruise'* to assign train drivers and train managers to duties, whereas the node based personnel planning (i.e. cleaning and assembly workers) is done manually. Again, a tool is used to visualise the planned scheme (Fleuren, 2019).

Cooperation between NS and ProRail

The interdependency between NS and ProRail is not only limited to NS requesting railway paths from ProRail. Aside from the infrastructure capacity allocation, ProRail also controls the railway traffic and maintains the infrastructure. Good cooperation and coordination between the two parties is thus of high importance.

In order to better understand the relationship between NS and ProRail, their history should be briefly inspected. Until 1995 the management of infrastructure and the execution of railway operations were both owned by NS. In 1995, NS was split, with NS taking over the execution of railway companies, and the former NS departments *Railinfrabeheer*, *Railned*, and *Railverkeersleiding* became responsible for the railway infrastructure management, maintenance, and rail traffic coordination. In 2002, the separation between management and operation became also organisationally definitive. In 2005, the three merged infrastructure related departments started to work under the name of ProRail B.V. (ProRail, 2019). This vertical separation was instilled by EU rules in order to increase competition in the rail industry. However, a vertical separation can also cause incentive misalignments due to different goals of the companies. Especially in case of investments and higher train densities, good alignment becomes of major importance (Van de Velde, 2018).

While ProRail is a product driven organisation with an engineering culture, NS is a service driven organisation with a customer oriented culture. Consequently, their priorities diverge. Safety represents the first priority of ProRail, followed by the aim to increase the robustness and punctuality of the railway system. NS, on the contrary, puts the passenger first and strives towards an attractive door-to-door service (Fukken, 2018). Furthermore, it should be noted that the contracting structure of the Dutch railway system can be seen as a triangle between NS, ProRail and the Ministry of Infrastructure and Water Management. The railway objective balance, which includes the key focus of each of the three parties, is visualised in Figure 3.3.

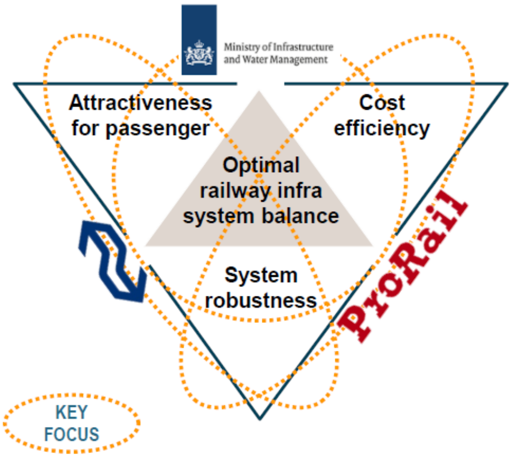


Figure 3.3: Railway objective balance (Fukken, 2018)

Figure 3.3 shows that both NS and ProRail strive to achieve a robust railway system. In addition, NS wants to reach attractiveness for passengers, whereas ProRail focusses on cost efficiency. The Ministry of Infrastructure and Water Management represents the mediator as its key role is to create a balance between the three objectives. According to Fukken (2018), however, the ministry did not adequately manage the conflicting views. Therefore, ProRail and NS grew apart leading to suboptimal cooperation and imperfections on strategic, tactical, and operational level. Consequently, the program *'Better for More'* was introduced in 2012 in order to improve the cooperation between NS and ProRail by formulating common goals. *Better for More* aims to improve the train services (i.e. reliability and frequency) and the traffic management (i.e. faster response to disruptions), and increase the capacity for services and maintenance until 2028 step by step (Fukken, 2018). According to Van de Velde (2018), realignment arrangements such as *Better for More* may improve the situation yet not solve all issues of a vertically separated railway industry.

3.2. Servicing Planning

According to Anonymous (2019) each service location plans their own service tasks. As no standard working procedure exists for all service locations, there are partially large differences between SLs. Besides the rolling stock management for maintenance and service (MBN: *"Materieel Bestuur NedTrain"*), who has a national overview of all service locations in order to plan urgent service tasks on operational level, there is thus no centralised service planning. Moreover, the technical checks and exterior cleaning are planned independently from the interior cleaning tasks. The reason for this is that the interior cleaning is outsourced. Hence, the cleaning company Hago is responsible for the interior cleaning planning and the work planners do not have control of the interior cleaning execution.

Currently, the work planners use a planning system called *'Maximo'*. Maximo contains the BDU plan in order to create work orders. These work orders need to be approved by the work planners. The work planners enter a "yes" or "ok", or check off a task. Then, they need to enter the name of a technician or train driver to whom the task is assigned to. Subsequently, Maximo sends a work order towards the assigned blue colour worker. The work order created by Maximo indicates what type of cleaning should be performed at which RS unit. However, it does not say where and when the task must be executed. Hence, the blue colour workers need to make their own working schedule. The duration of a task may vary not only between different types of RS, but also between different RS units of the same type. This is due to different states of the RS units based on their previous executed service, their utilisation and age.

Furthermore, the work planners manually create a daily service plan in Excel, which involves the requests from the SD plan. Note that the BDU plan is a basic week plan for 8 weeks and significantly differs from the SD plan, which is the plan for the specific day. This Excel plan presents the current and the forecasted service planning from a specific moment in time. Every 8 hours (i.e. three times per day) such a planning snapshot is created. Even though urgent service requests occur on a daily basis, these updates are not implemented in the most recent Excel plan.

As the planning system Maximo and the Excel plan are not connected to each other, there is need of manually entering data, which takes a large amount of time. Instead of regular updates, they only make an overview at three time moments per day. Moreover, the visualisation of this overview is unsatisfactory.

In order to automate the service planning, the new project *'SLIM'* is developed. SLIM stands for *'systeem logistieke inzet materieel'* and describes a system that handles the RS usage from a logistical perspective. SLIM is still in its development phase, but it might be implemented very soon dependent on the performance of the test phase planned for end of October. SLIM uses the planning system Maximo by automatically entering the data of the SD plan from Donna. As the SD plan is already completed 56 hours in advance, the service planning can also be prepared 3 days in advance. All adaptations to the SD plan are directly updated in SLIM. The advantage of SLIM is also that it indicates the place and the time span of the requested service task. Furthermore, SLIM has a great visualised overview as shown in Figure 3.4.

As can be seen in Figure 3.4 on the left side of the display, the RS units, which are entering the SL, are listed as well as the train numbers in which they had been running. In the middle, the RS units are assigned to a certain track number and scheduled for a certain period of time in which it stands at that track. Note that multiple RS units may stand simultaneously at the same track (e.g. RS unit 8614 and 8627 are both standing on track 44 from 13:30 to 14:30 in Figure 3.4). With a red dashed line the current moment in time is highlighted in the planning overview. The RS units, which are at real time at the SL, are colour-coded (i.e. here in orange), whereas the forecasted RS visits are indicated in white-black. On the right side of the display, the RS units leaving the SLs are listed as well as the train numbers to which the RS units are assigned to. Note that the RS units do not necessarily leave the SL in the same order as they entered the SL, yet the order depends on the RS type and capacity the scheduled trains require. On top, there is a real time overview of the stabling and shunting yard, where all RS units standing recently at the SL are displayed.

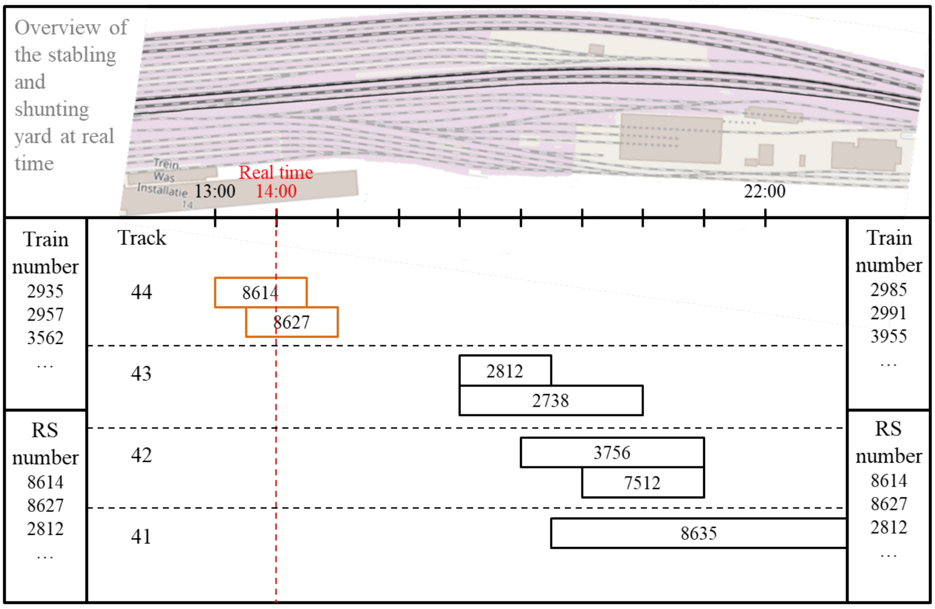


Figure 3.4: Visualisation of the planning system SLIM

Interior Cleaning

Anonymous (2019) explained that the main tasks of the interior cleaning involve the floors, tables, seats, toilets, and the emptying of the garbage bins. Although interior cleaning happens every day, the individual cleaning tasks vary in frequency (see Table 3.1). The emptying of garbage bins, for instance, happens at least once per day and is also performed at turning stations during daytime (*Dutch: keerpuntreiniging*). More effortful cleaning tasks are only performed at night at SLs. While toilets are also cleaned every day, the floor is cleaned twice per week. If necessary, the windows and walls are cleaned (i.e. approximately once per week). Occasionally, graffiti needs to be removed in the interior of an RS unit, yet this is not planned. Currently, there is a national plan indicating at which days which interior cleaning tasks need to be performed. Hence, it does not matter if an RS unit ends up at a different SL as the same cleaning tasks are executed at all SLs. However, if an RS unit skips, for instance, the floor cleaning due to disturbances and deviations from the plan, the RS unit would need to be taken out of its circulation during daytime leading to additional deviations from the plan. Otherwise, the floor of that RS unit is not cleaned for an entire week.

Interior cleaning task	**Frequency**
Emptying garbage bins	≥ once per day
Cleaning toilets	once per day
Cleaning tables	three times per week
Cleaning floors	twice per week
Cleaning seats	once per day
Removing graffiti	occasionally

Table 3.1: Frequencies per cleaning task

NS signed a contract with the interior cleaning company Hago saying that at least 70% of all RS units need to be spotlessly cleaned while the remaining 30% may be less clean in case of a lack in time. According to Anonymous (2019) this agreement is difficult to check as nobody from NS controls the interior cleaning. Even though an RS unit stood already clean at the SL for the entire day and was not cleaned in the specific night, Hago can count that RS unit as one of the spotlessly cleaned RS units. Furthermore, Anonymous (2019) said that passengers expect trains to have at least a primary purification. This is not the case at the moment, yet from January 2020 the interior cleaning system will change. The new system entails a primary purification for all RS units and individually adds cleaning tasks to RS units based on urgency.

In case a higher service demand is planned in advance, the SL can hire additional personnel. According to Anonymous (2019), there is no lack in personnel. However, due to a lack in communication and cooperation between the SD planners and the SLs as well as due to unforeseen work intensities per RS unit, it is possible that not all RS units can be fully serviced during the night shift. Therefore, *"dirty starters"* (*Dutch: vuile starters*) appear, meaning the RS units leaving the SL in the morning without being cleaned. Those dirty starters need to be taken out of their circulation during the day in order to be cleaned. This is the reason why 4 different types of daily cleaning services exist (NS, 2019f):

• DCR	(Dagelijkse Controle Reiniging)	daily control cleaning
• DC	(Dagelijkse Controle)	daily control
• DR	(Dagelijkse Reiniging)	daily cleaning
• DCW	(Dagelijkse Controle Watervullen)	daily control water refill

In principle, trains receive a DCR every 24 hours. However, it is possible that, for instance, the service time is too short for a DCR, so trains are scheduled for a DC or a DCW within operation times and a DR after operation at the platform. Trains which drive at night receive a DCR before departure (NS, 2019f).

Technical Checks

As mentioned before, there are mainly two types of technical checks, namely the A-check and the B-check. The B-check consists of visual inspections of major technical train components, such as the braking system and the wheels. In addition, the critical safety systems are checked on functionality. While most RS types need a B-check every second day, the A-check is more extensive and mostly performed every 12 days (Van Marsbergen, 2018). Note that if an A-check is planned, the B-check is not necessary. A two-week schedule may, thus, look as indicated in the following table.

Week 1				Week 2			
Monday	Wednesday	Friday	Sunday	Tuesday	Thursday	Saturday	Monday
A-check	B-check	B-check	B-check	B-check	B-check	A-check	B-check

Exterior Cleaning

For an exterior cleaning, an RS unit needs to drive through a Train Washing Machine (TWM). According to Van Marsbergen (2018), twelve of the thirty NS service locations are equipped with a TWM. Even though the desired frequency of the exterior cleaning is once per week, the deadline is regularly not met. This is due to the fact that the exterior cleaning is not considered a critical task, which means that trains can still operate if the deadline has passed.

Furthermore, the removal of graffiti is also considered to be an exterior cleaning task. Only a few service locations have the equipment required for a graffiti removal. This type of exterior cleaning does not have a regular frequency due to its unexpected nature, yet it should be removed as quickly as possible (Van Marsbergen, 2018).

Set up of Trains

Every night after trains completed servicing, they need to be formatted in order to leave the next morning in the right composition. For each train a certain number of a certain type of RS units is planned and this plan needs to be realised at the SLs. Due to the lack in physical capacity at the SLs, shunting tasks should be minimised. Therefore, trains should not only be stabled in the right composition, but also in the right order in which they leave the SL. Even though the shunting movements are planned as precise as possible, operational changes (e.g. timetable changes) can cause adaptations to the plan leading to additional shunting tasks (Van Marsbergen, 2018).

Capacity Issues at NS Service Locations

The service locations have a maximum stabling and service capacity. While the stabling capacity is measured in number of rail carriages that can be stabled per moment, the service capacity refers to the number of rail carriages that can be serviced per night (i.e. between evening and morning peak hour) (Grunbauer, 2019). As the critical service time is at night, the capacity indication is only available for the night and not for daytime. Currently, there is little personnel available during daytime as RS is mostly not serviced during daytime. According to Fleuren (2019) and Anonymous (2019), hiring more personnel during daytime should not represent a problem. It is more an issue that sufficient RS units need to be available for daytime servicing in order to pay off the additional personnel.

The busiest service locations are those located in the Randstad. As can be seen in Figure 3.5, the service locations in Utrecht, Amsterdam, and The Hague have by far the highest service demands (i.e. more than 200 rail carriages per night) followed by Rotterdam, Zwolle, and Eindhoven (i.e. more than 100 rail carriages per night) (Topal, 2019). Multiple service locations feature a higher service demand than service capacity. In those cases, rail carriages are assigned to other service locations that can provide additional service capacity at night and otherwise during daytime (i.e. DCR) (Grunbauer, 2019). The total service capacity of all service locations together exceeds the service demand by 358 rail carriages. However, according to NS estimations (Topal, 2019), the total service demand will increase by over 1000 rail carriages per night until 2030. Hence, the current capacity will definitely not be sufficient by then. Without increasing capacities, the service locations at Utrecht, Arnhem, The Hague, and Zwolle will show major shortages in capacity (see Figure 3.5). Note that there are two SLs located in Amsterdam as well as in Utrecht, whereas in Figure 3.5 those SLs are combined (i.e. 28 of the total 30 SLs are listed in Figure 3.5).

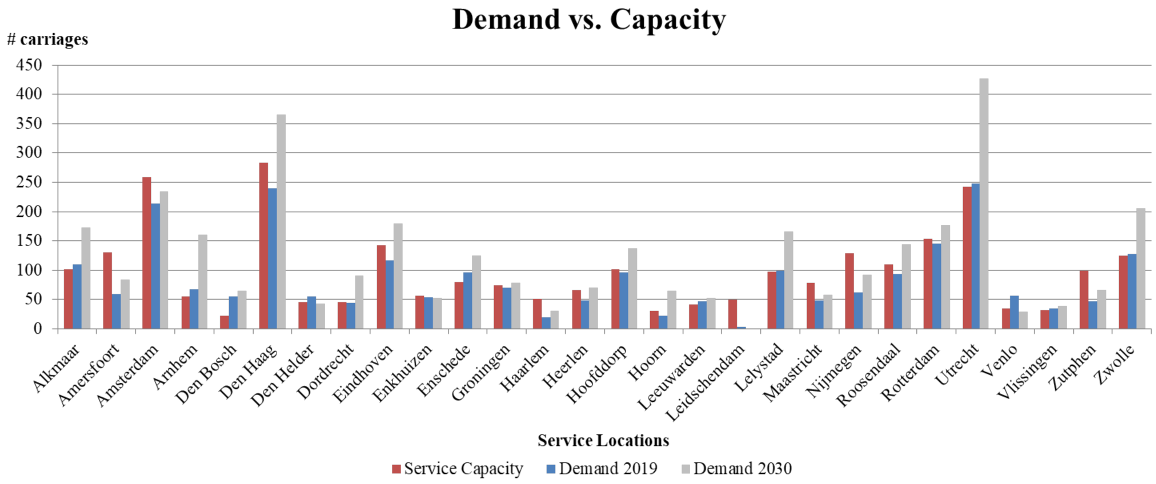


Figure 3.5: Service demand versus capacity according to Grunbauer (2019) and Topal (2019)

Note that there are also environmental restrictions (*Dutch: milieuvergunning*) with respect to stabling and servicing capacities at service locations. This has mainly to do with noise pollution during shunting. The environmental capacity restrictions vary between service locations (Grunbauer, 2019). In case NS wants to extend the capacity at a service location at night, the environmental capacity might present a problem. When extending the daytime service capacity, the environmental capacity will not present an obstacle as the environmental restrictions are less strict during daytime. Furthermore, by shifting service demand from night towards daytime, the service capacity at night would not need to be extended and NS would not need to worry about complying with the environmental capacity anymore.

According to Schemmekes & Van Heusden (2019), the physical capacity at the service location in Eindhoven is fully used at night. Only if everything goes according to plan, it fits perfectly. However, unplanned shunting or stabling of additional rolling stock units is not or almost not possible. As described before, interruptions happen on a daily basis which may lead to deviations from the plan dependent on the situation (i.e. line closures, events, available RS, and personnel). Mr. Scheffers, the coordinator of the RS planning of NS explained that internally the National Control Centre (*Dutch: Landelijk BesturingsCentrum*) daily publishes a KPI called "RS use according to plan" (MivP) (*Dutch: "materieelinzet volgens plan"*) (Scheffers, 2019). The MivP describes in percentages to what extent the actual RS usage is executed according to the SD plan. Actually, there are two percentages measured: one at the start of the operational day (90.7%) and one at the end (86.5%). However, the MivP measures only whether a train runs in the right train composition (i.e. right number of RS units and right RS type) on time on the right route, but it does not capture the specific RS unit nor does it consider at which platform a train stands or at which stabling track an RS unit parks at night. According to Schemmekes & Van Heusden (2019), it is currently not possible to uncover the actual operational execution at a node. Therefore, there is no estimation quantifying to what extent the train operations follow the (SD) plan. Upon asking, the responses of the operational controllers vary drastically.

Due to deviations from the plan, the stabling request may thus exceed the perfectly fitting stabling capacity and enlarge the problem that RS units cannot be cleaned at night. According to Schemmekes & Van Heusden (2019), planners from the SL often complain about dirty starters. An increase in capacity is thus highly necessary.

Furthermore, Schemmekes & Van Heusden (2019) see high potential in servicing trains during daytime as there are many rolling stock units out of operation between the morning and evening peak (i.e. between 9:30 and 15:00). However, they said that daytime services would need to be incorporated in the planning in order to prevent uncoordinated approaches during operation. In addition, good coordination between RS controllers, train drivers, and SLs would be essential.

3.3. Coordination between RS and Servicing Planning

According to Fleuren (2019), each plan product (i.e. BD, BDU, SD) is forwarded to the service locations. By doing so, the SLs get informed about the RS planning already in an early stage and can check for feasibility. However, the processing of the plan products by the service locations mostly exceeds the moment in time at which their feedback could be directly applied to the corresponding plan product. Hence, adjustments on the BD plan from the side of the service locations are received too late to incorporate them into the BD plan. However, adjustments of the BD plan can be considered in the BDU. As the product plans are updated frequently (i.e. every 2 months), only early reactions from the service locations can be taken into consideration. Certainly, the BD plan is easier to be adjusted for an entire year because there is only one basic week plan. Modifying the year plan within the BDU, on the contrary, would be 6 times as arduous since there are 6 BDUs per year. Hence, this implies higher computational work, which is time consuming and costly.

In the operational phase, service locations and rolling stock planners have different objectives, which cause a difficult cooperation between the two entities. While the main objective of the service locations is to provide fully functional and clean rolling stock units, the rolling stock planners need to ensure that the right train is at the right moment at the right location available for operation (Schemmekes & Van Heusden, 2019). The service locations, for instance, try to receive specific rolling stock units, which require service. Hence, they request the rolling stock controllers to take those specific rolling stock units out of circulation. For the rolling stock controllers, however, their first priority is to comply with the timetable, followed by their second priority to maintain the right train compositions. For the right train compositions, only the RS types play an important role, yet not the specific RS units. Only in case of a safety issue, the problem is considered as an acute problem and a rolling stock unit is directly taken out of the circulation. Otherwise, RS controllers try to send the RS unit at the end of the operational day towards a service location. In case of a lack of available rolling stock, the cleaning deadlines will be the first to be postponed.

3.4. Comparison to DB Regional

When searching for solutions, it is often interesting and useful to know if others face similar problems and if so how they cope with it. It is remarkable how little communication occurs between different railway companies. Nobody at NS could tell whether the German railway company Deutsche Bahn (DB), for instance, faces capacity issues with respect to their service locations. For this reason, an interview with DB Regional Bavaria was held in order to analyse their service planning. DB Regional Bavaria is selected due to comparable basic facts as shown in Table 3.2.

Basic Facts

NS and DB Regional Bavaria were juxtaposed with regard to a few basic facts, as shown in Table 3.2, in order to evaluate to what extent the two railway companies can be compared.

	NS [1]	**DB Regional Bavaria**[2]
Surface size[3]	41,543 km^2	70,550 km^2
Population	17.3 million	13.1 million
Track kilometres[4]	2,100 km	6,000 km
Train journeys per day	4,800	2,800
# Passengers per day	1.1 million	1.1 million
# RS units	700	920
Train categories	IC direct, IC, Sprinter	RE, RB, S-Bahn
Financial situation	partially subsidised by state [5]	subsidised by state
# Employees	36,600	3,770

Table 3.2: Comparison NS and DB Regional Bavaria regarding basic facts

As can be seen in Table 3.2 the surface size of Bavaria is almost twice as large as the Netherlands and the network size in track kilometres is almost three times as large. However, the population of the Netherlands is larger than Bavaria's and the number of passengers per day is the same for NS and DB Regional Bavaria. This is in line with the fact that the Dutch railway network is Europe's busiest railway network (Authority for Consumers & Markets, 2019). The train categories of NS and DB Regional are similar as the RE can be compared with the IC and the RB and S-Bahn with the Sprinter. NS and DB are both independent corporations with state ownership. As the state and the provinces have multiple requests with respect to the train schedule (e.g. relatively high frequencies for unprofitable train series) and fares (e.g. student discounts), NS receives subsidies in order to facilitate these requests (Algemene Bestuursdienst, 2017). While the long-distance railway of DB is profitable, the regional-distance railway is not and is therefore supported by contracting agencies and transport associations. DB Regional Bavaria, for instance, has a contract with the Bayerische Eisenbahngesellschaft (BEG), which is the railway authority in Bavaria owned by the state Bavaria. This means that DB Regional Bavaria can decide its own strategy conforming the contract with BEG (Van Wersch, 2019). The basic facts listed above show that NS and DB Regional Bavaria are comparable with respect to the number of passengers per day and train categories. Note that DB Regional Bavaria does not include cargo nor international train traffic as opposed to NS. Nevertheless, the large difference in number of employees is remarkable. Even though NS and DB Regional Bavaria are both subsidised, their financial situations are slightly different as DB Regional Bavaria is even more dependent on the subsidies of the state compared to NS.

Servicing Planning

In the following paragraph, the servicing planning of the DB Regional is described in comparison with NS. Figure 3.3 presents a direct comparison according to (Fleuren, 2019, Van Wersch, 2019).

As can be seen in Figure 3.3, the tasks executed at service locations are exactly the same. Also, the frequency of these tasks is very similar – only small technical checks feature different deadlines at NS in comparison with DB Regional Bavaria. It is worth mentioning that at DB Regional Bavaria a small technical check is executed by the train driver before and after usage. This check represents a very short control check. Even though such a control check is generally conducted twice a day, the minimum frequency is every 24 hours (see Table 3.3). Any larger technical checks are executed at maintenance depots rather than at service locations. At NS, however, there are 2 different types of technical checks executed at service locations. The B-check is relatively short (yet more intensive than the daily technical checks at DB Regional Bavaria) and executed every 48 hours. Also, a more extensive A-check is performed approximately every 12 days. Furthermore, DB Regional Bavaria differentiates

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[1] According to NS (2019a)

[2] According to Deutsche Bahn (2019) and Van Wersch (2019)

[3] The surface size refers to the surface of the Netherlands and of the state Bavaria, respectively.

[4] In terms of single track (i.e. a double track is counted twice)

[5] According to Algemene Bestuursdienst (2017)

between five interior cleaning levels. While the lowest level is executed every 24 hours, the most extensive cleaning level – comprising intensive seat cleanings – is performed once every 6 weeks. At NS, there is not such a differentiation in planned cleaning levels. In principle, a full interior cleaning is planned every 24 hours (i.e. DCR), yet in case of a lack in time, a shorter cleaning session is scheduled for the next day (i.e. DR, DC and DCW). However, from January 2020 NS will change towards a multiple level cleaning system. A primary purification will then be the basis for all trains and urgent cleaning tasks will be added individually (Anonymous, 2019).

	NS	**DB Regional Bavaria**
Tasks at SLs (incl. frequency)	small technical checks (48h), interior cleaning(24h), exterior cleaning (1 week) set-up trains (24h)	small technical checks (24h), interior cleaning(24h), exterior cleaning (1 week) set-up trains (24h)
Busiest period at SLs	at night	at night
Daytime servicing at SLs	(almost) none	only larger cleaning works
Interior cleaning levels	DCR, DR, DC, DCW	5 cleaning levels
RS circulation	weekly plan (BDU)	weekly plan
RS allocation	planned on day of operation	planned on day of operation
Preferred SL allocation	close to natural destination of RS unit	close to natural destination of RS unit
Capacity issues	servicing at night, stabling at night	intense cleaning at night, exterior cleaning at night
Coping with capacity issues	stabling RS units outside the SL, analysing possibilities for daytime servicing, cancelling cleaning tasks	expanding infrastructure of cleaning stages, using facilities for exterior cleaning also during daytime, using facilities of other SL, cancelling larger cleaning tasks
Main difficulties regarding daytime servicing	low RS availability, need for good planning, unpredictability, lost in flexibility	low RS availability, need for good planning, unpredictability, lost in flexibility

Table 3.3: Comparison NS and DB Regional Bavaria regarding service planning

Both railway companies face capacity issues at service locations at night. While at NS both the servicing and stabling capacity present shortages, DB Regional Bavaria does not face physical capacity issues as RS units can be stabled outside of the service locations at reserved tracks. Furthermore, the daily cleaning tasks do not present a capacity problem at DB Regional Bavaria because they can be executed at most stabling yards outside of service locations. Only for the more extensive cleaning tasks as well as for the exterior cleaning, DB Regional Bavaria has capacity bottlenecks at night. The reasons for these bottlenecks are a lack in time at night and a shortage in appropriate cleaning facilities. As each service location has only one exterior cleaning facility, there is a queue of rolling stock units with respect to their exterior cleaning deadline.

It is interesting to see how NS and DB Regional Bavaria cope with capacity issues. Ten Broek (2019) explained that in Alkmaar, NS is already stabling rolling stock outside the service location at night in order to make space for a second and third service shift. Recently NS has started to analyse the possibilities for daytime servicing, which this research also contributes to. DB Regional Bavaria, on the contrary, expanded the infrastructure of cleaning stages in order to increase the capacity for larger cleaning works. Furthermore, facilities for exterior cleaning are also used during daytime if rolling stock is available. Another way to cope with the capacity issues at DB Regional Bavaria is the efficient usage of the entire railway network. This means that other service locations can be visited in order to reduce the rush at a very busy service location. For both NS and DB Regional Bavaria, operating according to the timetable has the highest priority. Therefore, cleaning tasks are the first to be cancelled in case of a lack in time or RS availability.

When considering daytime servicing, multiple and comparable difficulties can be pointed out. The main issue seems to be the low RS availability, which is directly connected to the higher purpose of efficient RS usage incorporated in the rolling stock planning. Additionally, Fleuren (2019), Schemmekes & Van Heusden (2019), and Van Wersch (2019) expected that the implementation of daytime servicing requires very good planning. Furthermore, they said that the system is not predictable enough to plan the allocation of specific RS units as there are always operational adjustments. Actually, planning the allocation of specific RS units would not even be desirable because this would restrict the flexibility.

Learning Effects

When summing up the main differences between NS and DB Regional Bavaria, multiple learning effects can be highlighted. The following three solutions of DB Regional Bavaria could, for instance, also be applied at NS:

- Stabling RS units at stabling tracks outside of service locations
- Efficient usage of the entire railway network: balance work between busier and less busy service locations
- Using facilities for exterior cleaning during daytime

The solutions listed above are not entirely new for NS. As already mentioned, NS has started stabling RS units on reserved tracks outside of service locations in Alkmaar. NS also tries to efficiently use the entire railway network by shifting RS units to less busy SLs. However, there is still need for optimisation. It should be noted that balancing work between busier and less busy service locations may cause empty kilometres as RS units might need to drive empty in the evening towards another service location and in the next morning return empty in order to collect passengers from the starting station. At NS, the facilities for exterior cleaning are used during daytime in case RS units are at the SL and do not have any other tasks scheduled. However, as already mentioned the number of available RS units during daytime is very limited. The implementation of daytime servicing should be facilitated, which is exactly why NS is starting to analyse this.

A further two ideas represent different ways of coping with service planning by DB Regional Bavaria as opposed to NS:

- Splitting cleaning tasks into multiple intensity levels
- Conducting small technical checks before and after usage by train driver

In general, those ideas may also lead to a capacity increase at service locations. However, further research is required. More specifically, whether the benefits of the splitting of cleaning tasks into multiple intensity levels outweighs the negative consequences needs to be analysed. However, it would probably decrease the work intensity of the daily cleaning with a frequency of 24 hours. As this is the most critical service task at the moment, this solution seems favourable. Note that the interior cleaning system is going to change from January 2020 with respect to introducing multiple cleaning levels. As for the small technical control checks executed by the train driver before and after train usage, this could relieve the workload at the service locations at night. However, again further analysis is necessary to ascertain whether safety requirements are fulfilled when the current technical checks performed by technicians will be replaced by control checks by train drivers.

As a last learning effect, DB Regional Bavaria also expanded the infrastructure of cleaning stages. Unfortunately, this solution might not be applicable to NS because of spatial restrictions in the Netherlands. The spatial restrictions also result of the high population density (see comparison of surface size and population in Table 3.2). However, further research might be desirable.

3.5. Rolling Stock Exchange Concept

Concluding from the paragraphs above, daytime servicing represents a favourable solution for the capacity problems at NS service locations at night. There are two important challenges with respect to allowing trains to be serviced during daytime. On the one hand, there is a lack in rolling stock available for servicing during daytime. Hence, more rolling stock units should be available at service locations in order to make daytime servicing efficient (e.g. to make it worthy to have servicing personnel at an SL during daytime). On the other hand, as the interior of rolling stock needs to be cleaned every 24 hours, it means that if a rolling stock unit is cleaned during daytime on the one day, it should also get cleaned on the following day during daytime. However, this represents a complex puzzle as a certain rolling stock unit does not have the same route every day but circulates through the entire Dutch railway network (B. Huisman & Zomer, 2019).

Certainly, it is possible to plan that each rolling stock unit has the same route every day (or every weekday) ensuring that a certain rolling stock unit passes the same stations at the same moment in time every day. However, such a strict planning would not be flexible enough in case of disturbances and imposes multiple restrictions. This makes it an undesirable option.

A solution needs to be found that increases the number of rolling stock units available for servicing during daytime and ensures meeting the 24 hour cleaning deadline for each rolling stock unit. This might be done by bringing more rolling stock units to the service locations during daytime. The idea is to exchange operating rolling stock units, which require servicing with serviced rolling stock units being in reserve at service locations during daytime. As the number of rolling stock units per train is higher in the peak hours as compared to the off-peak hours, rolling stock units stand in reserve at service locations between the morning and evening peak for a duration of between 2 and 8 hours. These residual rolling stock units could be cleaned directly after entering the service locations and might then be exchanged with operating rolling stock units which have not been serviced at that day so far (and thus require service). The goal of the rolling stock exchange concept is to maximise the number of rolling stock units being serviced during daytime. By means of this aim, the chance of meeting the 24 hour cleaning deadline increases for the rolling stock units being serviced during daytime.

As mentioned before, the frequency of the interior cleaning of rolling stock is approximately 24 hours. Technical checks, on the contrary, have a frequency of 48 hours and exterior cleaning is in general executed once a week or even only once over multiple weeks. Ensuring regular daytime servicing is thus essential for interior cleaning, whereas it plays a minor role for technical checks, let alone for exterior cleaning. Furthermore, the interior cleaning is performed by the external company Hago, which is dependent on the number of rolling stock units provided by NS during daytime. Hence, NS sees high relevance in increasing the number of rolling stock units available for interior cleaning during daytime in order to improve the capacity usage at service locations. However, the rolling stock exchange concept assumes that if a rolling stock unit visits a service location during daytime, it is fully serviced with respect to all service deadlines. In this way, the rolling stock units being serviced during daytime do not require any further service at night and can thus be stabled separately from rolling stock units requiring night services.

In order to avoid passengers having to change trains, RS units should only be exchanged at turning points.

Van Wersch (2019) said that the most effective way to increase the capacity issues at SLs at night is to allow daytime servicing. However, he was sceptical about the RS exchange concepts as it increases the workload with respect to shunting, planning, and coordination between RS controllers and service locations. Additional train drivers might be needed in order to perform the RS movements between the stations and the SLs.

Moreover, Fokkenrood & Gerritzen (2019) said that the RS Exchange concept would require a large number of additional train drivers. This is due to the fact that walking distances at SLs are rather large and after a train driver will have brought an RS unit towards an SL, he would be out of service for approximately one hour.

Anonymous (2019) is in favour about the idea to increase the number of RS units visiting the SL during daytime as this may lead to more efficient daytime shifts of technicians and train drivers. However, a new problem might occur by randomly exchanging RS units. This problem refers to the maintenance planning of each RS unit, which is planned with respect to a certain number of kilometres or days. The maintenance work is already taken into account in the BDU plan, but if RS units are exchanged, multiple RS units might run more kilometres and others fewer kilometres than actually planned. Hence, the maintenance deadlines may also change. When implementing such an RS exchange concept, it is important to take the adaptation of the maintenance deadline into account.

Moreover, the acceptance of a dirty RS unit is higher in the afternoon than in the morning. According to Anonymous (2019), passengers react more critical towards malodorousness and dirt in the morning than in the afternoon. When considering shifting the night cleaning towards daytime, primary purifications would need to be performed before each train trip in order to please passengers. These primary purifications might be executed at the turning station of a train. This would present a notable change of the current cleaning system but may increase the passenger satisfaction to a large extent.

Schemmekes & Van Heusden (2019) were also very positive about daytime servicing as that could avoid dirty starters (i.e. dirty RS units in the morning) when cleaning tasks have been skipped at night due to unforeseen circumstances. Planning and coordination were addressed as requiring optimisation when implementing the RS exchange concept in order to prevent uncoordinated approaches during operation. This may relate to the cooperation between RS controllers and SL managers as well as between NS and ProRail. Note that the decision support model developed in the framework of this master thesis for the RS Servicing Scheduling Problem should support an optimal planning.

4

The Rolling Stock Servicing Scheduling Problem

In this chapter the third and fourth subquestion are approached: *"What information, knowledge and data is required for a decision support model?"* and *"Which functions should a decision support model feature in order to improve the capacity usage at service locations?"*. First, in Section 4.1, the type of the model is specified. Then, in Section 4.2 the RS-SSP is described by means of a simple example. The example helps to understand which decisions the model has to take and what the input and output of the model are. In Section 4.3, the model components are defined and explained and, finally, Section 4.4 provides the mathematical formulation of the model including the objective function and constraints.

4.1. Model Type

Regarding the model type, an optimisation model was chosen instead of a heuristic approach. The reason for this is based on the benefits of an optimisation model, which achieves best possible solutions and is flexible for changes in input parameters. As the model will be used in the tactical planning phase, higher computation times are less interfering as, for instance, in the operational planning phase.

Chapter 2 showed which type of models have been used in literature for similar conceptual formulations. Mainly, two exact optimisation approaches are used in literature. On the one hand, the Maximum Bipartite Matching problem is converted to a flow network and solved by an algorithm finding the maximum flow in the network. On the other hand, Mixed Integer Linear Programming models are developed to solve, for instance, the minimum cost problem. While the matching problem can be used for simple problems, the MILP model is also suitable for very complex problems. The advantage of the former is that the calculation time is very fast, so multiple scenarios can be performed in a short time.

In order to decide on the type of model, it is necessary to evaluate whether or not the Maximum Flow Problem is suitable for the RS-SSP. This depends on the theoretical capacity of the RS-SSP. If the problem is non-polynomial solvable, the Maximum Flow Problem may not be able to yield an optimal solution.

The problem definition of the RS-SSP has similarities with the Multi Depot Vehicle Scheduling Problems and the Multiple Vehicle Type VSPs from literature. Kliewer et al. (2006) proved that the multi-depot case of the VSP is NP-hard. Also, Lenstra & Kan (1981) and Bertossi et al. (1987) showed that a vehicle scheduling problem with multiple vehicle types is already NP-hard without multiple depots. As the RS-SSP does incorporate both multiple service locations and multiple RS types, the RS-SSP can be described as NP-hard. Even though the Maximum Flow Problem could probably be used for the model developed in the framework of this master thesis as part of a greedy algorithm, which might achieve suboptimal and relatively fast results, a MILP model can be more easily extended in a later state. Therefore, the MILP model is considered as more suitable for the RS-SSP.

4.2. Problem Description

The Rolling Stock Servicing Scheduling Problem described earlier needs to be technically defined in order to allow a formulation in a mathematical way. Within this master thesis, the RS-SSP is described for a basic scenario consisting of a single train series, a homogeneous RS fleet (i.e. single RS type), and a single service location (e.g. Zwolle). By means of this scenario, the model can be formulated straightforwardly with a limited number of parameters and variables. Further investigations may then focus on the extension of the model in order to allow multiple RS types and multiple service locations.

It is important to understand the functionalities of the model. Therefore, the conceptual model can be visualised as in Figure 4.1.

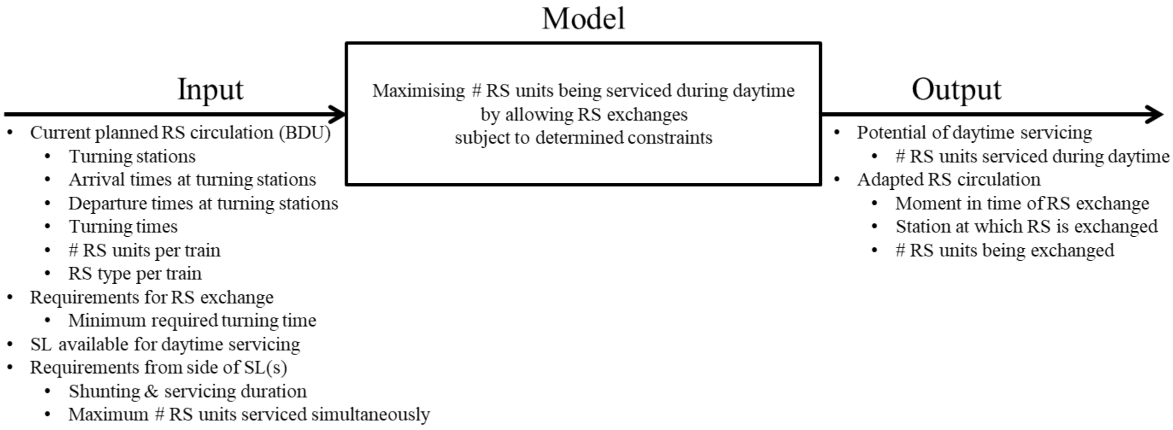

Figure 4.1: Conceptual model

A conceptual model comprises the input and output of the model as well as the function of the model itself. In Figure 4.1, the list below the arrow indicating the input of the model contains all important parameters, which are considered as being known. Those input parameters are all based on data and estimations given by NS. The RS circulation of the BDU plan (NS, 2019e), for instance, entails the routing of a single RS unit including the turning stations with its arrival and departure times and resultant turning times. As the RS units are assigned to trains, the train compositions with number of RS units and types are given as well. The minimum required turning time for an RS exchange of 10 minutes is based on an estimation of B. Huisman & Zomer (2019). This estimation considers the shunting and coupling duration of RS units at a turning station. A service location poses requirements regarding the servicing duration and the shunting duration between the station and the SL as well as within an SL. Note that the shunting and servicing duration is aggregated and thus represents one single parameter. Also, the maximum number of RS units which can be serviced simultaneously is provided by the SL. Those two requirements are specified per SL (Grunbauer, 2019). The model developed in this thesis assumes a single SL to be available for daytime servicing. This assumption significantly decreases the complexity of the model. Which SL is available for daytime servicing depends on the selected train series.

The box in Figure 4.1 contains the mathematical model for solving the RS-SSP. The model consists of the objective function to be optimised (i.e. maximising the number of RS units being serviced during daytime) and the underlying constraints, which need to be met. The RS-SSP model contains multiple functionalities. In contrast to current operations, it allows RS units rolling out towards the SL to be serviced during daytime. Moreover, RS units standing at the SL are not provided for operations unless they have completed servicing. Also, RS exchanges are possible between serviced and servicing requiring RS units. Thanks to RS exchanges, the number of RS units visiting the SL can be increased achieving a higher objective function. Furthermore, it takes the capacity at the SL into account (i.e. maximum number of RS units, which can be serviced simultaneously) as well as the shunting and servicing duration. Also, the RS-SSP respects the train arrival and departure times given by the timetable and it tracks the RS circulation.

As opposed to the input parameters, the output of the model entails results which are not known in advance as they depend on the function of the model (see "Output" in Figure 4.1). More precisely, the output gives the values for each decision and auxiliary variable. The output of the RS-SSP entails the total number of RS units being serviced during daytime (i.e. objective value). Furthermore, it indicates which RS unit visits the SL at what time. Note that the BDU plan does distinguish between RS units yet does not specify the physical RS unit. Hence, RS units are just enumerated.

Figure 4.2 visualises the matching between operating trains and RS units standing on reserve at an SL, and the model decisions to be taken. The circles in grey represent trains in operation and the circles in blue indicate RS units at an SL. Circles of the same shade represent the same train or RS unit respectively. The visualisation shows the sorting from a large number of available trains and RS units towards a small selection of suitable trains and RS units, which allow possible matches. Ultimately, each train can only be assigned to one RS unit and the other way around, so a decision needs to be taken to determine the train and the RS unit selected for the RS exchange. In the example of Figure 4.2, four trains arrive at time t at turning station j. Only two of the four trains feature a turning time larger than the minimum required turning time for an RS exchange. As only one (i.e. indicated with the dark grey circle) of the two remaining trains consists of an RS unit which has not yet been serviced, it is the only train with RS exchange potential at time t. From the four RS units standing at the SL at time t, two RS units (i.e. the two darker blue circles) have completed servicing and are available for an RS exchange. As the train with RS exchange potential has only one RS unit requiring servicing, only one RS exchange can be executed at time t. Therefore, the model may randomly select one of the two possible matches (indicated as lines) to decide which RS units are exchanged. The outcome is one RS exchange (i.e. indicated as a red line) at time t at station j.

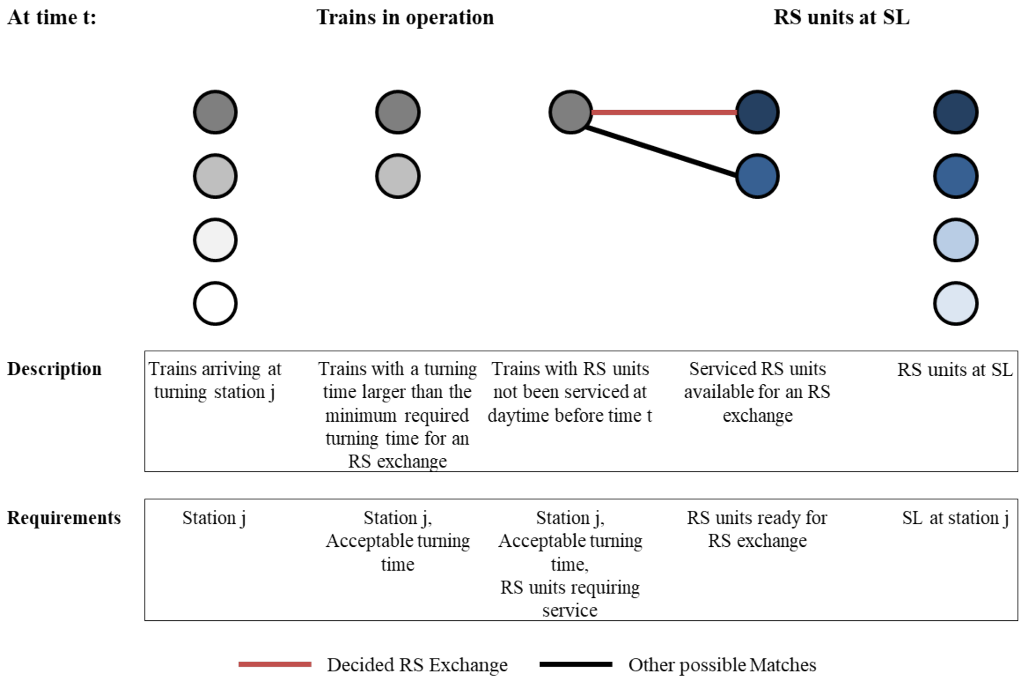

Figure 4.2: Visualisation of the decisions taken by the model

According to the BDU plan from 4.02.2019 (NS, 2019e), the train series 5600 commutes between Utrecht and Zwolle using 11 RS units as indicated by the different colours in Table 4.1. The cycle time, which is the duration from the moment that a train departs from Zwolle until it returns to Zwolle, is 2 hours and 43 minutes. All trains visible in the timetable of Table 4.1 feature the same cycle times. On the first day of the week (i.e. on Monday) the first train starts at 5:23 from Zwolle to Utrecht and the last train departs at 23:53 from Zwolle (and arrives at 1:11 in Utrecht). The trains start operating with two RS units until the end of the morning peak hour. Note that there is one exception where a train departs from Zwolle at 05:53 with a train length of 1 RS unit. After 09:00 each arriving train is decoupled at Zwolle, where one RS unit is driven towards the SL and the other RS unit runs in the subsequent departing train back to Utrecht. In total, 5 RS units are driven to the SL and the remaining 6 RS units keep commuting between Utrecht and Zwolle. At 14:53 one of the RS units standing on reserve at the SL in Zwolle is used again for operation (see Table 4.1).

Arriving train		**At the SL**	**Departing train**		
# RS units	**Arrival**	**# RS units**	**Departure**	**# RS units**	**Time**
		7	05:23	2	Morning peak
		5	05:53	1	
		4	06:23	2	
		2	06:53	2	
2	07:06	0	07:23	2	
2	07:36	0	07:53	2	
2	08:06	0	08:23	2	
1	08:36	0	08:53	1	Transition *RS units out of operation*
2	09:06	1	09:23	1	
2	09:36	2	09:53	1	
2	10:06	3	10:23	1	
2	10:36	4	10:53	1	
2	11:06	5	11:23	1	
1	11:36	5	11:53	1	Off-peak *RS units exchangeable*
1	12:06	5	12:23	1	
1	12:36	5	12:53	1	
1	13:06	5	13:23	1	
1	13:36	5	13:53	1	
1	14:06	5	14:23	1	
1	14:36	5	14:53	2	Transition *RS units into operation*
1	15:06	4	15:23	2	
1	15:36	3	15:53	2	
1	16:06	2	16:23	2	
1	16:36	1	16:53	1	
1	17:06	1	17:23	1	
2	17:36	1	17:53	1	Evening peak
2	18:06	1	18:23	1	
2	18:36	1	18:53	1	
2	19:06	1	19:23	1	
1	19:36	1	19:53	1	Evening & night operations
1	20:06	1	20:23	1	
1	20:36	1	20:53	1	
1	21:06	1	21:23	1	
1	21:36	1	21:53	1	
1	22:06	1	22:23	1	
1	22:36	1	22:53	1	
1	23:06	1	23:23	1	
1	23:36	1	23:53	1	
1	00:06	1			
1	00:36	1			

Table 4.1: Arrival and departure times at Zwolle according to NS (2019e)

As can be seen in Table 4.1, the morning peak is defined as the time period where the arriving and departing trains are running with two RS units. From 08:36 the *Transition phase* starts with a single RS unit train arriving at Zwolle. The following arrival trains are all decoupled at Zwolle and are thus in transition from running with a length of 2 RS units to running with a length of 1 RS unit. In this morning transition phase several RS units are going out of operation. From 11:36 until 14:23 the off-peak period is defined. In this period all arriving and departing trains run with a length of 1 RS unit. The off-peak period is between the morning and the evening transition phase. As opposed to the morning transition phase, the trains arriving within the evening transition phase are extended by a second RS unit. Almost all RS units are in operation after the transition phase – one single RS unit remains at the SL. The period between 17:36 and 19:06 is defined as the evening peak, with the arrival trains running with two RS units. After 19:06 the evening and night operations take place. Note that the time period after the evening peak is not taken into consideration for daytime servicing as RS units rolling out to the SL after the evening peak are regarded as being night serviced. Assuming that no additional RS units are on reserve at the SL, the RS units are not available for exchanges before 11:06. This is because the first RS unit arrives at the SL at 09:06 and is serviced and ready for operation two hours later. Therefore, the period in which RS units can be exchanged starts at the arrival time of 11:06. As one RS unit remains at the SL during the evening peak, RS exchanges may also be possible during the evening peak hours.

Note that even though RS units are rolling out towards an SL after the morning peak, their interiors are currently not cleaned (Anonymous, 2019). Hence, the potential of full daytime servicing may increase from zero up to the maximum number of RS units operating in the train series 5600 (i.e. 11 RS units marked in different colours in Table 4.1). Whether all RS units can be serviced during daytime is not directly guaranteed. This is influenced by the number of available RS units standing on reserve at the SL. In the case presented in Table 4.1, for instance, there are 5 RS units at the SL. However, not all of them are already exchangeable at 11:06 when the first RS unit can be exchanged. Note that in the example shown in Figure 4.1, the first RS exchange occurs at 11:36 even though an RS exchange would have been possible at 11:06. This is because the example shows only one of multiple optimal solutions. Hence, the first RS unit arriving at the SL at 09:06 (marked in light blue) is exchanged with the RS unit arriving at 11:36 (marked in red), the second arriving RS unit (i.e. 09:36 marked in yellow) is ready for an exchange with the RS unit arriving at 12:06 (marked in blue), and so on. There are only 5 RS units rolling out towards the SL after the morning peak and at least 6 RS units are always in operation simultaneously. In this case, however, it is possible that the RS unit arriving at the SL at 11:36 will be exchanged with the train arriving at 14:06. All 11 RS units can be serviced during daytime according to the schedule presented in Table 4.1. Even though RS exchanges are possible in the evening transition phase and the evening peak due to remaining RS units standing at the SL, no RS exchange is required anymore because all RS units have already been serviced. Note that the RS unit circulation as marked in different colours in Table 4.1 is according to the BDU plan (NS, 2019e) until the first RS exchange (i.e. beginning with the departing train at 11:53).

The example described above provides an understanding of the minimum requirements of an RS exchange with respect to timing. Besides the timing, multiple restrictions can be added such as a maximum number of RS units being serviced at the same time at the SL. With the assumed servicing time of 2 hours, there are up to 4 RS units serviced at the same time in the previous described scenario. In case the maximum number of RS units being serviced simultaneously is lower than 4, the moments at which an RS exchange can occur differs from the scenario described above,

Furthermore, it is important to prevent RS units visiting an SL multiple times during daytime. In the scenario described above, all RS units visited the SL by 14:06. Afterwards, no RS unit should be exchanged anymore. Hence, RS units which have been serviced need to be marked in order to avoid double servicing.

4.3. Model Components

In this section, the components of the RS-SSP Base Model are defined consisting of parameters and variables. As the parameters and variables entail multiple indices, those indices including their sets need to be specified as well. The Base Model of the RS-SSP is based on multiple assumptions. Those assumptions are summarised in the list below:

- 1 single day
- 1 single service location
- 1 single RS type
- 1 single RS unit per train
- Trains are not (de-)coupled during their cycle time
- RS units start servicing immediately when entering the SL

Parameters

In the simple case of one train series, trains are commuting between two turning stations. Each train departing at one turning station and arriving at the other turning station has its own train number. In order to differentiate between trains, arriving trains are indexed with $k \in K^{arr}$ and departing trains are indexed with $l \in K^{dep}$. The differentiation between arriving and departing trains is necessary for tracking the RS circulation as described below. τ_k^{arr} is defined as the arrival time of train $k \in K^{arr}$. As the Base Model assumes that only one SL is available for daytime servicing, also only 1 turning station is of interest in this model. Hence, there is no need for defining an index for turning stations in the Base Model.

Furthermore, a phase is defined as the time period between two train arrivals. In order to track activities in time, an index $i \in I$ is defined as the phase until the next train arrives. The set I represents the set of all train arrivals at the turning station. Before the first train arrives at the turning station phase i is 0 and in the moment that the first train arrives i is 1 until the next train arrives. Hence, after each train arrival, i increases by 1. Note that the size of set I is the size of set K^{arr} plus one.

According to the example described in Table 4.1, it is assumed that all RS units are in operation during the morning peak. Therefore, no RS units are available for an RS exchange during the morning peak. For this reason, the RS-SSP concentrates on the time period after the morning peak. Thus, the phase $i = 1$ starts with the arrival of the first train after the morning peak. As RS units being serviced after the evening peak are not considered as daytime serviced anymore, the last phase ends with the last train arriving within the evening peak.

In order to assign the phase i with the arriving or departing train k or l, denote $arr(i)$ as the arriving train in phase i and $dep(i)$ as the departing train in phase i. Furthermore, the time of a train arriving in phase i can be denoted as $\tau_{arr(i)}^{arr}$. Note that the rolling stock circulation can be tracked by means of the index i.

Mostly, the routing of trains follow a cycle. This means that a train l departing from a turning station returns after a certain cycle time towards the same turning station as train k. It is assumed that no coupling or decoupling occurs during the cycle time of trains, so train l and train k make use of exactly the same rolling stock units. It is worth mentioning that a train departing in phase i does not implicitly return in phase $i + 1$ as trains may arrive in between the departure and the returning time of train l. Therefore, $\sigma(l)$ is denoted as the returning train of train l. Here, it becomes important to distinguish between arriving and departing trains. Note that the cycle of a train only considers the way from a train departing from a certain station until its returning train arrives at the same station, whereas the RS circulation takes the entire route of a certain RS unit into account. Depending on the time horizon, the RS circulation entails the allocation to specific train numbers including their departure and arrival stations, arrival and departure times, as well as turning times.

Each RS unit u is element of the set RS. Moreover, the specific RS unit running in train k is defined as RS_k^{spec}. Note that until the first RS unit gets exchanged, the RS circulation is according to the BDU plan. Obviously, the first arriving trains, which have no predecessor, run with the RS units given by the RS circulation of the BDU plan. In order to specify the RS circulation, the set K^{arr_0} is defined to consist of the first arriving trains without a predecessor.

The number of RS units initially standing at the SL is denoted as SL_0. Due to the assumption that all RS units are in operation during the morning peak, the number of RS units which already completed servicing in the initial phase ($i = 0$) is zero. The set of the specific RS units which are initially standing at the SL is defined as RS^{SL_0} and the time at which those RS units entered the SL is denoted by T_u^{in}. In addition, SL^{max} is the maximum possible number of RS units which can be serviced at the SL simultaneously.

Besides, it is important to identify the turning time tt_k of train k at the turning station in order to know whether an RS exchange can be executed. A train k is worth considering for an RS exchange if the turning time tt_k is at least as long as the minimum required turning time tt^{min}. The minimum required turning time tt^{min} is based on an assumption regarding the average duration of (de-)coupling and shunting at a turning station when executing an RS exchange.

Furthermore, the maximum shunting and service duration of a rolling stock unit is defined as one combined parameter d^{max}. This means that the maximum period of time is considered to shunt an RS unit u from the arrival platform of the station to the service location, execute all services required for that specific RS unit (i.e. including interior cleaning and if necessary a technical check, exterior cleaning and small reparations) including all RS movements at the service location, and shunt the

RS unit towards the departure platform of the train to which it has been assigned after having been serviced.

Variables

After having defined all important parameters with their indices and sets, the next step is to introduce the decision and auxiliary variables. The decision variables are crucial as they are unknown (i.e. variable) and the model outcome specifies what values they need to have in order to achieve the optimal objective value. Hence, they directly depend on the objective function. Also, the auxiliary variables are unknown, yet they are not important for decision making. In fact, they are used for tracking a specific information in time, such as the number of RS units standing on reserve at the SL or the moment at which an RS unit enters the SL. The decision variables may rely on those auxiliary variables, which makes them necessary.

The RS-SSP Base Model entails multiple binary decision variables. Those are defined as $y_{u,i} = 1$ if the unserviced RS unit u visits the SL at the start of phase i (i.e. $\tau^{arr}_{arr(i)}$), 0 otherwise; $y'_{u,i} = 1$ if the serviced RS unit u leaves the SL at the start of phase i, 0 otherwise; and $z'_{u,i} = 1$ if the serviced RS unit u stands ready at the SL at the start of phase i, 0 otherwise.

In addition, the Base Model also uses several auxiliary variables. The binary variable $x_{u,k} = 1$ if RS unit u runs in train k, 0 otherwise. Note that before the first RS exchange happens, $x_{u,k}$ is predefined by the BDU plan. From the moment of the first RS exchange, however, it becomes variable. The auxiliary variable $u_i \in \mathbb{Z}^+_0$ specifies the number of RS units, which are in service at the SL at the start of phase i.

In Figure 4.3 the decisions to be taken at the turning station are visualised, including the resulting RS movements. All variables are located at an arc or node within the figure. The figure shows a turning station consisting of four different nodes. The arrival (arr) at and the departure (dep) from the turning station represent the lower two nodes. The service location is represented by the upper two nodes, whereas the left one (u_i) counts all RS units which are being serviced in phase i. The right node is the assembling place for all RS units which have completed servicing. The arcs show how an RS unit may get from one to the other node. Starting from the arrival node, an RS unit u has two possibilities. In the case that $y_{u,i} = 0$, the RS unit u goes towards the departure node in order to run in the next departing train (i.e. $dep(i)$). In the case that $y_{u,i} = 1$, the RS unit goes towards the SL. In the RS-SSP Base Model it is assumed that each RS unit arriving at the SL can be serviced immediately after its arrival. Hence, the service duration starts at the moment at which the RS unit arrives at the SL. Assuming that the service duration lasts m phases, the RS unit u completes servicing in phase $i + m$. This means that the binary decision variable $z'_{u,i+m} = 1$ and that the RS unit u is subtracted from the assembly u_{i+m}. From the moment that the RS unit u completed servicing, it is available for an RS exchange. Therefore, at a phase $i + n$, where $n \geq m$, the decision variable $y'_{u,i+n}$ may turn 1. This means that the RS unit u leaves the SL and goes to the departing node in order to run in the next departing train $(dep(i + n))$. The variable $x_{u,l}$ indicates whether an RS unit u runs in the departing train l (i.e. $x_{u,l} = 1$) or not (i.e. $x_{u,l} = 0$). Note that the index i is used in order to keep track of the phase in time. This is mainly important for tracing the RS circulation. If train k, for instance, arrives in phase i (i.e. $k = arr(i)$) and RS unit u runs in train k $(x_{u,k} = 1)$, then the RS unit u may either run in train l departing in the same phase i (i.e. $x_{u,l} = 1$ with $dep(i) = l$) or enter the SL.

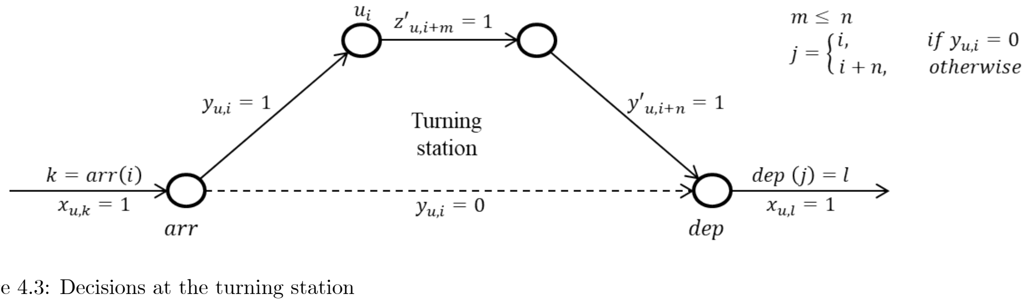

Figure 4.3: Decisions at the turning station

In Table 4.2 all model components are summarised for the RS-SSP.

Sets		
I	set of train arrivals [6]	
K^{arr}	set of arriving trains [6]	
K^{arr_0}	set of first arriving trains not having a predecessor [6]	
K^{dep}	set of departing trains [6]	
RS	set of all RS units [6]	
RS^{SL_0}	set of RS units standing initially at the SL [6]	
Indices		
i	phase between train arrivals	$i \in I$
k	arriving train	$k \in K^{arr}$
l	departing train	$l \in K^{dep}$
u	RS unit requiring service	$u \in RS$
Input parameters		
τ_k^{arr}	arrival time of train k [6]	[hh:min]
$\sigma(l)$	returning train of train l [6]	
$arr(i)$	arriving train in phase i [6]	
$dep(i)$	departing train in phase i [6]	
tt_k	turning time of train k [6]	[hh:min]
tt^{min}	min required turning time for exchanging RS units	[hh:min]
RS_k^{nr} [7]	number of RS units in train k	
RS_k^{spec}	specific RS unit running in train k [6]	
T_u^{in}	moment in time at which RS unit u entered the SL [6] [8]	[hh:min]
SL_0	number of RS units initially in service at the SL [6]	
SL^{max}	max possible number of RS units serviced at the SL simultaneously	
d^{max}	maximum shunting and service duration	[hh:min]
Decision variables		
$y_{u,i}$	= 1 if RS unit u visits the SL at the start of phase i, 0 otherwise	$y_{u,i} \in \{0,1\}$
$y'_{u,i}$	= 1 if RS unit u leaves the SL at the start of phase i, 0 otherwise	$y'_{u,i} \in \{0,1\}$
$z_{u,i}$ [9]	= 1 if RS unit u starts being serviced at the start of phase i, 0 otherwise	$z_{u,i} \in \{0,1\}$
$z'_{u,i}$	= 1 if RS unit u completed servicing at the start of phase i, 0 otherwise	$z'_{u,i} \in \{0,1\}$
Auxiliary variables		
$x_{u,k}$	= 1 if RS unit u runs in train k, 0 otherwise	$x_{u,k} \in \{0,1\}$
u_i	number of RS units in service at the SL at the start of phase i	$u_i \in \mathbb{Z}_0^+$

Table 4.2: Model components

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[6] Given by BDU (NS, 2019e)

[7] RS_k^{nr} is an input parameter used for the model extensions. It is defined in Section 4.4.2.

[8] Note that the moment in time given by T_u^{in} is prior to the arrival time of the first arriving train considered by the model. The RS units which feature such an early entering time are included in the set of RS units standing initially at the SL (RS^{SL_0}).

[9] $z_{u,i}$ is a decision variable used for the second model extension. It is defined in Section 4.4.3.

4.4. Model Formulation

In this section, the Rolling Stock Servicing Scheduling Problem is mathematically formulated. First, the RS-SSP Base Model is described in Section 4.4.1, then two model extensions are formulated in Sections 4.4.2 and 4.4.3.

4.4.1. RS-SSP Base Model

The RS-SSP Base model is first mathematically formulated and subsequently explained in words.

$$maximise \sum_{u \in RS} \sum_{i \in I} z'_{u,i} \tag{4.1}$$

subject to

$$y_{u,0} = 1 \ \forall u \in RS^{SL_0} \tag{4.2}$$

$$\sum_{u \in RS} y_{u,0} = SL_0 \tag{4.3}$$

$$x_{RS_k^{spec},k} = 1 \ \forall k \in K^{arr_0} \tag{4.4}$$

$$u_0 = z'_{u,0} = y'_{u,0} = 0 \ \forall u \in RS \tag{4.5}$$

$$u_{i+1} = u_i + \sum_{u \in RS} y_{u,i} - \sum_{u \in RS} z'_{u,i} \ \forall i \in I \tag{4.6}$$

$$u_i \leq SL^{max} \ \forall i \in I \tag{4.7}$$

$$y_{u,i} \leq x_{u,arr(i)} \ \forall u \in RS, i \in I \setminus \{0\} \tag{4.8}$$

$$x_{u,dep(i)} = y'_{u,i} + x_{u,arr(i)} - y_{u,i} \ \forall u \in RS, i \in I \tag{4.9}$$

$$x_{u,\sigma(l)} = x_{u,l} \ \forall u \in RS, \ \forall l \in K^{dep} \tag{4.10}$$

$$\sum_{u \in RS} x_{u,k} = 1 \ \forall k \in K^{arr} \tag{4.11}$$

$$y_{u,i} \cdot tt^{min} \leq tt_{arr(i)} \ \forall u \in RS, i \in I \setminus \{0\} \tag{4.12}$$

$$z'_{u,i} \cdot d^{max} \leq (\tau^{arr}_{arr(i)} - T^{in}_u) \ \forall u \in RS^{SL_0}, i \in I \tag{4.13}$$

$$z'_{u,i} \cdot d^{max} \leq (\tau^{arr}_{arr(i)} - \sum_{j=0}^{i} (y_{u,j} \cdot \tau^{arr}_{arr(j)})) \ \forall u \in RS \setminus RS^{SL_0}, i \in I \tag{4.14}$$

$$z'_{u,i} \leq \sum_{j=0}^{i} y_{u,j} \ \forall u \in RS, i \in I \tag{4.15}$$

$$y'_{u,i} \leq \sum_{j=0}^{i+1} z'_{u,j} \ \forall u \in RS, i \in I \tag{4.16}$$

$$\sum_{i\in I} y_{u,i} \leq 1 \ \forall u \in RS \tag{4.17}$$

$$\sum_{i\in I} y'_{u,i} \leq 1 \ \forall u \in RS \tag{4.18}$$

$$\sum_{i\in I} z'_{u,i} \leq 1 \ \forall u \in RS \tag{4.19}$$

$$\sum_{u\in RS} y_{u,i} = \sum_{u\in RS} y'_{u,i} \ \forall i \in I \setminus \{0\} \tag{4.20}$$

Formula (4.1) presents the objective function, which maximises the total number of rolling stock units which completed servicing during daytime. It is assumed that all rolling stock units are in operation at peak hours, so daytime servicing is only possible at off-peak hours between the morning and evening peak.

Constraints (4.2) to (4.5) set the initial values of the variables. Constraint (4.2) sets the initial decision variable $y_{u,0}$ to 1 for those RS units which are initially standing at the SL. Constraint (4.3) sets $y_{u,0}$ to 0 for all the remaining RS units. Furthermore, Equation (4.4) ensures that for the first arriving trains without a predecessor train for which the RS circulation is already known all $x_{u,k}$ are 1 if RS unit u runs in train k, 0 otherwise. Constraint (4.5) sets all remaining variables of phase $i = 0$ to zero.

Equation (4.6) tracks the number of RS units being in service in phase $i + 1$ by adding the number of RS units visiting the SL in phase i and subtracting the number of RS units which completed their service at the SL in phase i by the number of RS units being in service at the SL in phase i.

Constraint (4.7) ensures that the number of RS units being in service at the SL does not exceed the maximum number of RS units which can be serviced simultaneously during daytime at the SL (i.e. SL^{max}). Furthermore, an RS unit can only enter the SL in phase i if that RS unit runs in the train arriving in phase i. This constraint is formulated in the Inequation (4.8).

Equation (4.9) states that the RS unit running in the train departing in phase i is either the same as the RS unit leaving the SL in phase i or the RS unit which arrived in phase i. Note that in case of each of these scenarios, the other scenario is not applying.

Furthermore, the train composition does not change within the cycle time of a train. Thus, the same RS units are running in train l as in its returning train $\sigma(l)$. This is formulated in Equation (4.10). Equation (4.11) ensures that one RS unit is running in each scheduled train. This is according to the assumption that each train runs with a single RS unit.

Constraint (4.12) guarantees that RS units can only be exchanged if the turning time of the arriving train exceeds the minimum turning time. Constraints (4.13) and (4.14) track that $z'_{u,i}$ is only 1 if an RS unit u has been in the SL for a duration of the maximum service and shunting time (i.e. d^{max}). Constraint (4.13) focuses on the RS units which are initially standing at the SL and thus have an entering time T^{in} prior to the arrival time of the first arriving train. Therefore, $\tau^{arr}_{arr(i)} - T^{in}_{u}$ is always positive. Constraint (4.14), on the contrary, considers the RS units which are not initially standing at the SL. In order to avoid negative values on the right side of the Inequation, the length of stay at the SL is only observed of those RS units which have been standing at the SL before or in phase i. By means of Constraint (4.15), it is ensured that an RS unit can only be serviced in case it entered the SL. Without Constraint (4.15), $z'_{u,i}$ might turn one according to Constraint (4.14) for RS units which have never entered the SL. It might be worth mentioning that although $z'_{u,i}$ could always be zero according to Constraints (4.13) and (4.14), this will not happen as the objective function maximises the number of RS units which completed servicing.

With Constraint (4.16), it is ensured that an RS unit u only leaves the SL in case it has been fully serviced. Furthermore, RS units must not visit or leave the SL multiple times per day. Hence, Constraint (4.17) avoids that an RS unit u visits the SL more than once during the same day and Constraint (4.18) ensures that each RS unit leaves the SL at most once. In addition, Constraint (4.19) guarantees that no double servicing is done. And finally, Constraint (4.20) ensures that an RS unit can only enter the SL if another RS unit leaves the SL in the same phase.

4.4.2. RS-SSP with Multiple Units

In this section, an extension is made to the RS-SSP Base Model. The RS-SSP Multiple Units (RS-SSP-MU) enables that trains run with a length of more than 1 RS unit.

The RS-SSP Base Model assumed that all trains run with a length of one RS unit. However, the example of the BDU in Table 4.1 indicates that outside of the off-peak phase, trains are also running with 2 RS units. Without adjusting the timetable by assuming that all trains run with a length of one RS unit, the RS-SSP Base Model thus has a very limited time horizon (i.e. from 11:36 to 14:23). The time horizon for the RS-SSP-MU, however, can be as long as from 7:06 to 17:23. This time horizon starts with the first train arriving at Zwolle and ends with the last train departing from Zwolle before the evening peak.

In order to allow trains to run with multiple RS units, two constraints of the RS-SSP Base Model need to be adapted. Before formulating the extended model, an additional input parameter needs to be defined in order to specify the number of RS units running in train k. Let RS_k^{nr} be the number of RS units in train k according to the BDU plan. The extended model can then be formulated as:

$$maximise \sum_{u \in RS} \sum_{i \in I} z'_{u,i} \tag{4.21}$$

subject to (4.2)-(4.10); (4.12)-(4.19)

$$\sum_{u \in RS} x_{u,k} = RS_k^{nr} \ \forall k \in K^{arr} \tag{4.22}$$

$$\sum_{u \in RS} (y_{u,i} - y'_{u,i}) = (RS_{arr(i)}^{nr} - RS_{dep(i)}^{nr}) \ \forall i \in I \setminus \{0\} \tag{4.23}$$

As can be seen in the model formulation above, Constraint (4.11) is replaced by Constraint (4.22). Instead of limiting the number of RS units per train to one, the new parameter RS_k^{nr} specifies the number of RS units running in train k.

Furthermore, Equation (4.20) is replaced by Equation (4.23). Equation (4.23) ensures that the number of RS units entering the SL minus the number of RS units leaving the SL in phase i is equal to the difference in number of RS units running in the arrival and the departing train in phase i.

4.4.3. RS-SSP with Multiple Units and Waiting for Servicing

In this section the RS-SSP-MU is extended by the possibility that RS units wait at the SL for being serviced. Hence, the servicing duration might start at a later stage as compared to the moment that the RS unit enters the SL. The second extended model is called RS-SSP-MU-W, whereby the 'W' stands for waiting for servicing.

Both the RS-SSP Base Model and the RS-SSP-MU assume that an RS unit entering the SL will directly be serviced. However, in reality this might not be the case. Insufficient cleaning platforms, personnel, or equipment may be reasons for a limited number of RS units being in service simultaneously. In the RS-SSP Base Model and the RS-SSP-MU RS units would not be allowed to enter the SL in case the maximum number of RS units is being serviced at that moment. Sometimes this restriction may lead to a dismissed possibility of cleaning an RS unit. By allowing RS units to wait for being serviced, additional RS units might be serviced during daytime.

For the RS-SSP-MU-W, a new binary decision variable needs to be introduced. $z_{u,i}$ is 1 if RS unit u starts being serviced at the start of phase i, 0 otherwise.

Figure 4.4 visualises the extension of the RS-SSP. Instead of two nodes representing the SL as in Figure 4.3, the SL consists of 3 nodes (see Figure 4.4). After arriving at the turning station (arr) at phase i, an RS unit u has still two options: departing in train $dep(i)$ (i.e. $y_{u,i} = 0$) or entering the SL (i.e. $y_{u,i} = 1$). When entering the SL, however, the RS unit might need to wait until it is serviced. Therefore, an additional node is created. Phase $i + p$ is the phase in which the RS unit u starts being serviced (i.e. $z_{u,i+p} = 1$). Note that p indicates the number of phases in which the RS unit u needs to wait at the SL until it starts being serviced. Obviously, it is possible that p is 0, meaning that the RS unit u can directly be serviced when entering the SL. From the moment that the RS unit u starts being serviced at the assembly node u_{i+p}, the procedures equal that described in Figure 4.3.

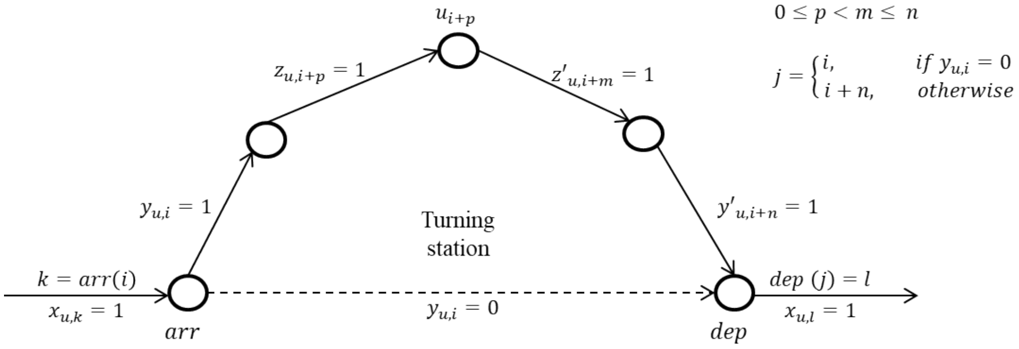


Figure 4.4: Decisions at the turning station when allowing RS units to wait at the SL before being serviced.

In the following, the RS-SSP-MU-W is mathematically formulated. Note that the first extension allowing trains to run with multiple RS units is also included in the RS-SSP-MU-W.

$$maximise \sum_{u \in RS} \sum_{i \in I} z'_{u,i} \tag{4.24}$$

subject to (4.2)-(4.5); (4.7)-(4.10); (4.12)-(4.13); (4.16)-(4.19); (4.22)-(4.23)

$$z_{u,0} = 0 \ \forall u \in RS \tag{4.25}$$

$$u_{i+1} = u_i + \sum_{u \in RS} z_{u,i} - \sum_{u \in RS} z'_{u,i} \ \forall i \in I \tag{4.26}$$

$$z'_{u,i} \cdot d^{max} \le (\tau^{arr}_{arr(i)} - \sum_{j=0}^{i} (z_{u,j} \cdot \tau^{arr}_{arr(j)})) \ \forall u \in RS \setminus RS^{SL_0} \tag{4.27}$$

$$z'_{u,i} \le \sum_{j=0}^{i} z_{u,j} \ \forall u \in RS, i \in I \tag{4.28}$$

$$z_{u,i} \le \sum_{j=0}^{i+1} y_{u,j} \ \forall u \in RS, i \in I \tag{4.29}$$

$$\sum_{i \in I} z_{u,i} \le 1 \ \forall u \in RS \tag{4.30}$$

Equation (4.25) fixes the initial value of the new variable $z_{u,0}$ by setting it to zero. Furthermore, Equation (4.26) replaces Equation (4.6). While Equation (4.6) increases the number of the assembly u_{i+1} when the sum of $y_{u,i}$ over all RS units u is positive, Equation (4.26) counts the sum of $z_{u,i}$. Regarding the difference between Figure 4.3 and Figure 4.4, the replacement of Equation (4.6) by Equation (4.26) becomes clear. Due to the possibility that RS units wait for being serviced after entering the SL, the decision whether an RS unit will be serviced is not taken by y anymore, but by z.

Constraint (4.14) is replaced by Constraint (4.27) as it is required to track the moment in time an RS unit starts being serviced rather than the moment in time it entered the SL in order to know whether the RS unit completed servicing.

Also, the Inequation (4.15) is replaced by Constraint (4.28) ensuring that an RS unit cannot complete service before having started being serviced.

Constraints (4.29) and (4.30) are additions to the RS-SSP defining the limits of the new variable $z_{u,i}$. Similar to the Inequation (4.28), Constraint (4.29) ensures that an RS unit can only start being serviced if it entered the SL before. Note that the option of servicing an RS unit immediately when entering the SL is still available. Finally, Constraint (4.30) ensures that each RS unit will only be serviced once.

5

Computational Experiments

After developing the mathematical model, the RS-SSP model was coded in Python using Jupyter Notebook as interface and Gurobi as solver. Subsequently, the model was applied to the Sprinter train series commuting between Zwolle and Utrecht (i.e. train series 5600). This train series was chosen because of its high consistency in the RS circulation. As opposed to other train series, the RS units used in the train series 5600 normally stay within this train series. Therefore, the RS units can easier be traced. Note that RS units leaving the train series cannot be traced when focusing on one single train series. Multiple scenarios regarding this train series were created and applied to the RS-SSP Base Model, the RS-SSP-MU, and the RS-SSP-MU-W. While Section 5.1 focuses on experimenting with the Base Model, Section 5.2 entails a comparison of the three models. By conducting experiments, the fifth subquestion – *"What adaptations at NS may support the applicability of the RS-SSP?"* – can be partly answered. More precisely, the answer relates to timetable changes and adjustments of servicing performances, which are considered by the input parameters of the model.

5.1. Scenarios Applied to the RS-SSP Base Model

According to the BDU plan, 5 RS units roll out towards the SL in Zwolle after the morning peak because trains arriving at Zwolle with a length of 2 RS units are decoupled in order to depart as trains consisting of only 1 RS unit. The trains arriving at Zwolle station feature mostly a turning time of 17 minutes, whereas the turning times in Utrecht are usually 7 minutes. These circumstances as well as the high traffic at and around Utrecht station, leading to very limited access paths to the SL in Utrecht during daytime, are reasons for choosing Zwolle as only available SL with respect to the model application. Various scenarios were selected in order to test whether the RS-SSP model works as defined in Section 5.1.1. Then, in Section 5.1.2, the model results are given per scenario and in Section 5.1.3 the results are further analysed and structured in order to see the impact of parameter changes on the model results.

5.1.1. Definition of Scenarios

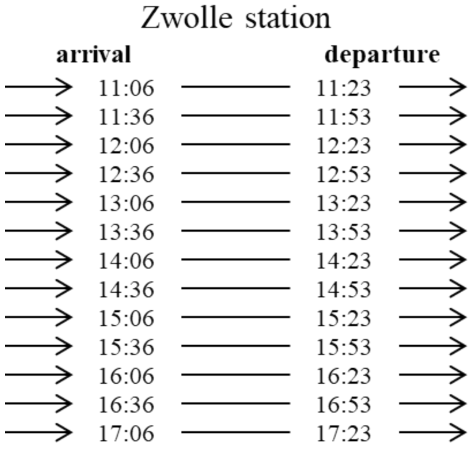
Firstly, the Monday scenario as given by the BDU plan is applied by the RS-SSP Base Model. The advantage of this scenario is that it was taken as example in Table 4.1. An optimal outcome (through manually resulting outcomes) had already been identified. This made it easy to calibrate the model against the optimal outcome. While multiple parameters were given by the BDU plan (see Table 4.2), the minimal turning time (tt^{min}) was specified according to estimations by B. Huisman & Zomer (2019). The maximum shunting and servicing duration (d^{max}) is based on servicing data for Zwolle (Topal, 2019). The maximum number of RS units being serviced at the SL simultaneously (SL^{max}) is chosen with respect to the number of RS units initially standing at the SL (SL_0). Note that it is assumed that there are no remaining RS units standing at the SL during the morning peak. Hence, SL_0 is given by the BDU plan as it indicates which RS units roll out towards the SL after the morning peak.

Table 5.1 shows the values of important input parameters for the first scenario. The first scenario is taken as *'Base Scenario'*. Note that the irregular numeration of RS units is based on the planned RS circulation. According to the BDU plan, RS units 4, 6, 7, and 9 are not operating on Monday. Furthermore, the timetable as given by the BDU plan (see Table 4.1) needed to be adjusted for application of the RS-SSP Base Model. This is because the RS-SSP Base Model assumes that trains run with a length of only one RS unit. All arriving and departing trains with a length of 2 RS units are thus replaced by trains running with a single RS unit.

τ_k^{arr}	{11:06, 11:36, ..., 17:06}	[hh:min]
T_u^{in}	{09:06, 09:36, ..., 11:06}	[hh:min]
RS	{1, 2, 3, 5, 8, 10, 11, 12, 13, 14, 15}	
RS^{SL_0}	{1, 3, 11, 14, 15}	
SL_0	5	
tt_k	00:17	[hh:min]
tt^{min}	00:10	[hh:min]
d^{max}	02:00	[hh:min]
SL^{max}	5	

Table 5.1: Parameter values for the Base Scenario

The timetable considered by the Base Scenario is visualised in Figure 5.1. The arriving trains are displayed on the left side of the figure, the departing trains on the right side. A single arrow stands for a train running with a single RS unit. As can be seen in Figure 5.1, all trains run with only one RS unit according to the assumptions of the RS-SSP. Furthermore, the arrival and departure times as indicated in Figure 5.1 range over the time horizon considered by the RS-SSP (i.e. from 11:06 to 17:23).



Zwolle station

arrival	departure
11:06	11:23
11:36	11:53
12:06	12:23
12:36	12:53
13:06	13:23
13:36	13:53
14:06	14:23
14:36	14:53
15:06	15:23
15:36	15:53
16:06	16:23
16:36	16:53
17:06	17:23

Figure 5.1: Timetable of the Base Scenario for experimentation with the RS-SSP

Further scenarios are based on the Base Scenario yet deviate by one or multiple changed input parameter(s). The parameters can be distinguished by the input data given by the timetable (i.e. τ_k^{arr}, T_u^{in}, RS, RS^{SL_0}, SL_0, and tt_k) and the constraining parameters (i.e. tt^{min}, d^{max}, and SL^{max}).

As can be seen in Table 5.1, the Base Scenario starts with the train arriving at 11:06 and ends at 17:06. The reason for this selected time horizon is based on the RS units being available for an RS exchange. As described in Section 4.2, the first RS unit rolls out towards the SL at 9:06 and at the earliest could run in the train departing at 11:23, when assuming a shunting and servicing duration of two hours. The predecessor train of the train departing at 11:23 arrives at Zwolle at 11:06 – the first arriving train considered by the Base Scenario. The last arriving train considered by the Base Scenario is the last train arriving before the start of the evening peak.

Furthermore, the Base Scenario assumes that trains arrive every 30 minutes. In total, 11 RS units are used, of which 5 RS units are initially standing at the SL. The moment in time at which those RS units entered the SL lies between 9:06 and 11:06 with a frequency of every 30 minutes. The turning times of the trains are consistently 17 minutes. For the Base Scenario the minimum turning time required for allowing an RS exchange is 10 minutes, the servicing and shunting duration is 2 hours and the maximum number of RS units being serviced simultaneously is 5.

In order to test whether the RS-SSP model works appropriately and delivers efficient results, multiple scenarios have been selected based on changes in input parameters as presented in Table 5.2.

	Changing parameter	**Values**
1.	headway [min]	[15, 30, 60]
2.	$\#RS$	[7, 8, ..., 18, 20]
3.	SL_0	[1, 2, ..., 6, 8, 14]
4.	tt_k [hh:min]	[00:10, 00:17]
5.	tt^{min} [hh:min]	[00:10, 00:17, 00:20]
6.	d^{max} [hh:min]	[00:30, 01:00, 02:00, 03:00]
7.	SL^{max}	[1, 2, ..., 6, 8, 14]

Table 5.2: Changing parameter values for different scenarios

Table 5.2 shows 7 changing parameters (see rows 1. to 7.) and the different values per parameter (see column *Values*). The Base Scenario consists of a combination of specific parameter values. On the one hand, scenarios were created with only one single parameter changed with respect to the Base Scenario. On the other hand, scenarios were selected consisting of multiple parameter adaptations. The scenarios selected for the RS-SSP Base Model are listed in Table 5.3.

The scenarios described in Table 5.3 show a wide variation of single and multiple parameter changes with respect to the Base Scenario. While many experiments were executed with different values for SL_0 and SL^{max}, only a few experiments focus on tt_k and tt^{min}. The lower interest in turning time experiments is based on the obvious outcome. As the parameter changes apply to all train services, $tt_k \geq tt^{min}$ does not present any restrictions to the model, whereas $tt_k < tt^{min}$ does not allow any RS exchanges at all. Increasing the values of SL_0 calls for increases in SL^{max}. Otherwise, an infeasible solution can be expected because more RS units than the allowed number are forced to get serviced simultaneously.

Changes in the total number of RS units mostly influence other parameter adaptations and vice versa. Note that in the Base Scenario 6 RS units are continuously in operation and 5 RS units are standing at the SL. As the RS-SSP assumes that the number of entering and leaving RS units is equal for each phase, the number of operating RS units never changes. Moreover, the returning train of a departing train from Zwolle arrives at Zwolle after 5 other train arrivals have been counted in the meanwhile. This means that 6 RS units are required in order to operate all train services as given by the BDU plan. Increasing or decreasing the number of RS units standing initially at the SL does not change the number of operating RS units. Therefore, a change in SL_0 directly influence the total number of RS units ($\#RS$) and vice versa. Besides, a change in train frequency impacts the number of operating RS units. Doubling the train frequency, for instance, implies a double number of operating trains. As the RS-SSP assumes that each train has a length of one RS unit, doubling the number of trains also means doubling the number of operating RS units. Regardless of the RS units standing at the SL, 12 RS units would be required in order to allow all train operations with a double frequency (i.e. headway of 15 minutes instead of the regular 30 minutes).

Scenario	**headway**	$\#RS$	SL_0	tt_k	tt^{min}	d^{max}	SL^{max}
Base Scenario	30	11	5	00:17	00:10	02:00	5
Scenario 2-5	30	11	5	00:17	00:10	02:00	1-4
Scenario 6	30	11	5	00:17	00:10	01:00	5
Scenario 7	30	11	5	00:17	00:10	00:30	5
Scenario 8	30	11	5	00:17	00:10	03:00	5
Scenario 9	30	11	5	00:10	00:10	02:00	5
Scenario 10	30	11	5	00:17	00:17	02:00	5
Scenario 11	30	11	5	00:17	00:20	02:00	5
Scenario 12	30	10	4	00:17	00:10	02:00	5
Scenario 13	30	9	3	00:17	00:10	02:00	5
Scenario 14	30	8	2	00:17	00:10	02:00	5
Scenario 15	30	7	1	00:17	00:10	02:00	5
Scenario 16	30	12	6	00:17	00:10	02:00	6
Scenario 17	30	20	14	00:17	00:10	02:00	14
Scenario 18	60	8	5	00:17	00:10	02:00	5
Scenario 19	15	17	5	00:17	00:10	02:00	5
Scenario 20	15	16	4	00:17	00:10	02:00	5
Scenario 21	15	15	3	00:17	00:10	02:00	5
Scenario 22	15	14	2	00:17	00:10	02:00	5
Scenario 23	15	13	1	00:17	00:10	02:00	5
Scenario 24	15	18	6	00:17	00:10	02:00	6
Scenario 25	15	20	8	00:17	00:10	02:00	8

Table 5.3: Scenarios applied to the RS-SSP Base Model

5.1.2. Model Results per Scenario

By applying the scenarios to the RS-SSP Base Model, multiple findings were obtained. Here, multiple measures are reported and evaluated, such as the objective function and several statistical values. While the objective function is a direct output of the model, the statistical values are calculated based on an analysis of the resulting variable values provided by the model. It is worth mentioning that the resulting variable values show insights into the RS movements as suggested by the model. Note that in case of infeasibility, no feasible solution exists. Table 5.4 provides the numerical solutions per scenario including the objective value and multiple statistics.

As can be seen in Table 5.4, the observed measures are the objective function (i.e. total number of RS units which completed servicing), the average number of RS units standing at the SL per moment in time, the average number of RS units being serviced per moment in time, the average duration per RS unit standing at the SL, and the average servicing duration per RS unit being serviced. In addition to the model outcomes of the Scenarios applied to the RS-SSP Base Model Table 5.4 also provides information about the original BDU plan. As mentioned before, no RS units are being serviced during daytime at the moment (i.e. objective function and average number of RS units being serviced are zero). However, in total 5 RS units are rolling out towards the SL during daytime according to the BDU plan leading to an average number of 3.5 RS units standing at the SL per moment in time between 7:06 and 00:36 or 3.8 when considering a time horizon from 11:06 to 17:06. The higher average value for the shorter time horizon is based on the start of the off-peak phase. All five RS units rolling out towards the SL are standing at the SL from 11:06. Taking the previous time period into account, where fewer or no RS units are standing at the SL, decreases the average value. Moreover, the average duration of an RS unit standing at the SL is 5:30.

The outcomes per scenario can be compared to the original BDU plan as well as to other scenarios. Scenarios 2 to 5 lead to an infeasible solution. This is a logical result because SL_0 is larger than SL^{max}. This means that 5 RS units are put initially into the SL, all being serviced immediately even though less than 5 RS units are actually allowed to be serviced simultaneously. Due to the infeasibility of Scenarios 2 to 5, those scenarios can be excluded from the further comparison.

Scenarios	**OF**	**avg #RS at SL**	**avg #RS being serviced**	**avg duration at SL** [10]	**avg duration being serviced** [10]
Original BDU	0	3.5 [11]	0	5:36	0:00
Base Scenario	11	5.0	4.2	3:10	2:43
Scenario 2-5	inf	-	-	-	-
Scenario 6	11	5.0	3.7	3:10	2:27
Scenario 7	11	5.0	3.6	3:10	2:24
Scenario 8	10	5.0	4.3	3:30	3:03
Scenario 9	11	5.0	4.2	3:10	2:43
Scenario 10	11	5.0	4.2	3:10	2:43
Scenario 11	5	5.0	5.0	7:00	7:00
Scenario 12	10	4.0	3.0	2:54	2:18
Scenario 13	9	3.0	2.8	2:30	2:23
Scenario 14	7	2.0	1.92	2:12	2:08
Scenario 15	4	1.0	1.00	2:00	2:00
Scenario 16	12	6.0	4.92	3:25	2:52
Scenario 17	20	14.0	10.00	4:39	3:15
Scenario 18	8	5.0	2.50	4:15	2.30
Scenario 19	15	5.0	4.71	2:23	2:09
Scenario 20	13	4.0	3.63	2:12	2:02
Scenario 21	10	3.0	2.92	2:15	2:10
Scenario 22	7	2.0	1.96	2:10	2:08
Scenario 23	4	1.0	1.00	2:00	2:00
Scenario 24	17	6.0	5.67	2:24	2:17
Scenario 25	20	8.0	6.96	2:40	2:20

Table 5.4: Results of RS-SSP Base Model

Starting with comparing the objective function, it is clear that all scenarios feature higher values than the original BDU plan. The lowest value of the objective function obtained by the RS-SSP model is 4 (see Scenarios 15 and 23). Scenarios 15 and 23 have different headways and the total number of RS units being in operation also varies. Yet both scenarios have only one RS unit initially at the SL ($SL_0 = 1$). The value of SL_0 seems to be crucial for the results of all measures for Scenarios 15 and 23 as they are all identical. It is worth mentioning that the RS-SSP Base Model assumes that the number of RS units standing at the SL never changes within the time horizon. This is based on Constraint (4.20) stating that an RS unit can only enter the SL if another RS unit leaves the SL in the same phase. Therefore, the average number of RS units standing at the SL is always an integer value as opposed to the original BDU plan. This also means that the average number of RS units standing at the SL per moment in time is equal to the maximum and minimum number of RS units within the entire time horizon. This value, thus, equals always the initial value SL_0.

The average number of RS units being serviced simultaneously can never exceed the number of RS units standing at the SL per moment in time. Mostly, the average number of RS units being serviced simultaneously is lower than the number of RS units standing at the SL. Only for Scenarios 15, 23, and 11 these values are exactly the same. This means that within the entire time horizon (i.e. 11:06 to

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[10] The average duration is given in [hh:min]. Note that the average is only taken over the RS units, which have been visiting the SL.

[11] Note that the 3.5 is the average number of RS units standing at the SL with respect to a time horizon from 7:06 to 00:36. When considering a time horizon from 11:06 to 17:06, this value is 3.8 and for a time horizon from 7:06 to 17:06 it is 2.8.

17:06), all RS units standing at the SL are being serviced.

Furthermore, the average duration per RS unit standing at the SL is naturally larger or equal to the average servicing duration per RS unit. This is because the average duration per RS unit standing at the SL entails both the duration of servicing and the duration of just standing at the SL without being serviced. It is important to understand that the average servicing duration as indicated in Table 5.4 differentiates from the required servicing (and shunting) duration as given by the input parameter d^{max}. Note that the RS-SSP model would never mark an RS unit as having completed servicing in case its duration at the SL is lower than the minimum required servicing duration d^{max}. However, an RS unit which has been standing at the SL longer than the minimum required servicing duration can still be marked as not having completed servicing. Only at the moment that an RS unit leaves the SL, it has to be marked as completed servicing. Due to this characteristic, the average servicing duration resulting from the model can be higher than d^{max}. It can be remarked that the difference in time between the servicing duration resulting from the model and the minimum required servicing duration (i.e. d^{max}) can be used as buffer for servicing personnel.

None of the scenarios feature any RS units with a lower servicing duration than d^{max}. This means that the model only sends RS units towards the SL in case the RS unit can complete servicing within the given time horizon. This observation refers to the objective function, which only counts the RS units having completed servicing within the time horizon. Scenarios 11, 15, and 23 are again the only scenarios having equal values for the average duration at the SL and the average servicing duration. While for Scenarios 15 and 23 this duration is exactly d^{max}, for Scenario 11 it is 7 hours. Note that the reason why this duration can be even longer than the duration of the entire time horizon (i.e. 6 hours) is because the servicing duration of the RS units standing initially at the SL is here also taken into account.

In order to better understand the meaning of the observed measures and to see how the objective value can be reached by complying with the constraints, the RS movements were visualised. First, Figure 5.2 shows the original RS movements according to the original BDU plan. Then, Figures 5.3 to 5.5 show the RS movements for diverse scenarios. Note that even more scenarios are visualised in the appendix (see Figures B.1 to B.3b).

On the y-axis of Figures 5.2 to 5.5, the RS units are indicated, whereas on the x-axis a timeline is given. It can be seen that the original plan features a time horizon starting at 7:06 with the first train arriving at Zwolle and ending at 00:36 with the last train arriving at Zwolle. In contrast, the RS-SSP Base Model only considers a time horizon starting at 11:06, when all RS units have been rolling out towards the SL. The considered time horizon ends at 17:06 before the start of the evening peak. The solution obtained by the RS-SSP Base Model only takes the part within the red coloured marking into account indicated by *time horizon*. As the model assumes all trains to run with a single RS unit, the RS movements after 14:36 do not comply with the original timetable. The time period before 11:06 as marked in grey is only visualised in order to show when the RS units initially standing at the SL entered the SL. Moreover, the RS arrivals at Zwolle station before 11:06 are according to the original BDU plan. The RS circulation after 17:06, however, differs from the original BDU plan. This is due to a larger number of RS units standing at that moment at the SL, which is a consequence of assuming single unit trains. As the time period after 17:06 is not within the time horizon of the RS-SSP, the resulting RS movements after that moment in time remain unknown.

Figure 5.2 shows that RS units 15, 14, 3, 1, and 11 enter the SL between 9:06 and 11:06. All of them are standing at the SL without being serviced (marked green). Furthermore, the operating RS units arrive at Zwolle station every 3 hours. From 11:06 until 14:36 all 5 RS units are standing at the SL, while in the meanwhile 6 RS units are continuously in operation. After 14:36, one after the other RS unit standing at the SL starts operating again - only one RS unit (i.e. RS unit 11) stays at the SL until the end of the day. From 11:06 until 14:36 trains run with a length of 1 RS unit. Before and after that time period, trains also run with 2 RS units. Trains arriving with a length of 2 RS units can be recognised by two light green crosses per moment in time, whereas trains departing with a length of 2 RS units can be recognised by two dark green crosses per moment in time. In case of a single cross per moment in time, the train runs with only one RS unit. Note that at the end of a green bar the corresponding RS unit leaves the SL and runs in the next train departing from Zwolle station. This RS unit is coupled with another RS unit in case that RS unit departs from Zwolle at the same moment in time. This is thus the case from 14:36 until 16:06. From 17:36 RS units are again rolling out towards the SL because trains start anew running with a single RS unit. The last six operating RS units roll out towards an SL from 23:36. RS unit 10 and 5, however, do not roll out at Zwolle yet at Utrecht (as marked in reddish). Below the time line, there are three more measures traced per moment in time (after a train arrival). The three measures consist of the number of RS units being in operation, the number of RS units standing at the SL and the number of RS units being serviced. Note that the sum of the number of RS units being in operation and standing at the SL is constant and represents the total number of used RS units. According to the original BDU plan, this sum is 11.

After having analysed the RS movements of the original BDU plan, the Base Scenario as visualised in Figure 5.3 can be investigated and contrasted with the original plan. It can be seen that the entering times of the RS units initially standing at the SL are exactly the same as compared to the original plan. This is because these entering times are input parameters of the RS-SSP. Also, the first RS arrivals within the considered time horizon equal the original plan. However, the RS units standing initially at the SL are being serviced as opposed to the original plan (i.e. blue marking) and are leaving the SL as soon as they have completed servicing. At the moment at which one RS unit leaves the SL an operating RS unit enters the SL and starts being serviced. RS unit 12, for instance, is exchanged by RS unit 15 and RS unit 13 is exchanged by RS unit 14. According to the model characteristics, the numbers of RS units being in operation and standing at the SL are constantly 6 and 5, respectively. The number of RS units being serviced, however, changes over time. As mentioned earlier, the servicing duration resulting from the model can vary from the minimum required servicing duration d^{max}. The different length of blue bars visualise the varying servicing durations. Note that servicing durations longer than d^{max} can be considered as buffer time. Hence, the corresponding RS unit could be serviced anytime within the indicated servicing time.

It should be remarked that all measures provided in Table 5.4 can be extracted from Figures 5.2 to 5.5. The objective function, for instance, is the sum of all blue bars. The average number of RS units standing at the SL is the average value of all numbers of RS units standing at the SL per moment in time. Note that even though the number of RS units standing at the SL (i.e. #RS at SL) is highlighted in green in the figures below the timeline, this measure entails both the RS units being serviced (blue bars) and the RS units standing at the SL not being serviced (green bars). Moreover, the average servicing durations (or the average duration at the SL) as listed in Table 5.4 are average lengths of all blue bars (or of all blue and green bars).

Scenario 11 presents a case, where no RS exchange is possible at all due to longer turning times than the minimum turning time required for an RS exchange (see Figure 5.4). All of the RS units standing initially at the SL are serviced, yet none of the operating RS units ever enters the SL. Due to a lot of buffer time, the servicing duration is extremely long for all of the RS units (i.e. between 6 and 8 hours). This is also reflecting in the average servicing duration given by Table 5.4.

In Figure 5.5, the RS movements of Scenario 15 are visualised. Remember that Scenario 15 sets SL_0 to 1. Therefore, RS units 14, 3, 1, and 11 are taken out (as marked in grey). Since only 1 RS unit is initially standing at the SL, the operating RS units need to wait as long as the RS unit standing at the SL completed servicing. RS unit 12 can be directly exchanged for RS unit 15, yet RS unit 13, 8, and 2 cannot be exchanged when arriving at Zwolle at 11:36, 12:06 and 12:36, respectively. Not until RS unit 10 arrives at Zwolle at 13:06, RS unit 12 completed servicing and is ready for an RS exchange. It can be seen that no buffer time is left in Scenario 15. For this reason, the average servicing duration equals the minimum required servicing duration as mentioned before.

Additionally to the measures mentioned above, the calculation time of the RS-SSP Base Model was also traced. For all scenarios the calculation time was lower than 1 second and thus very fast.

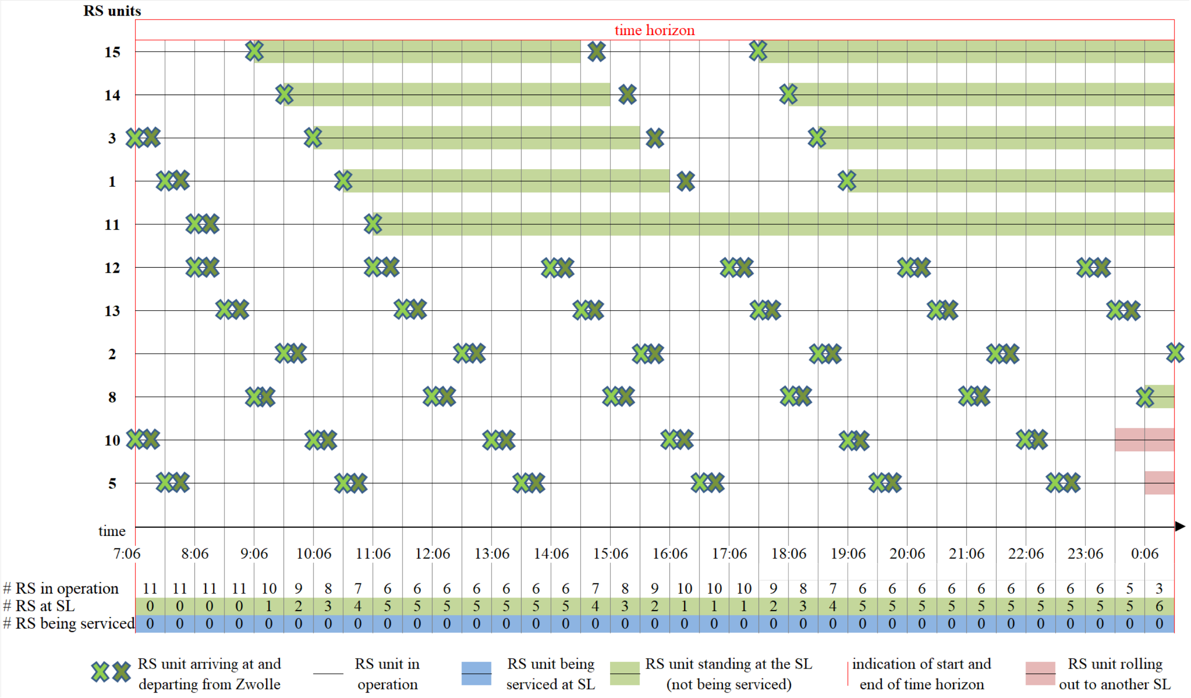


Figure 5.2: RS movements – Original BDU Plan

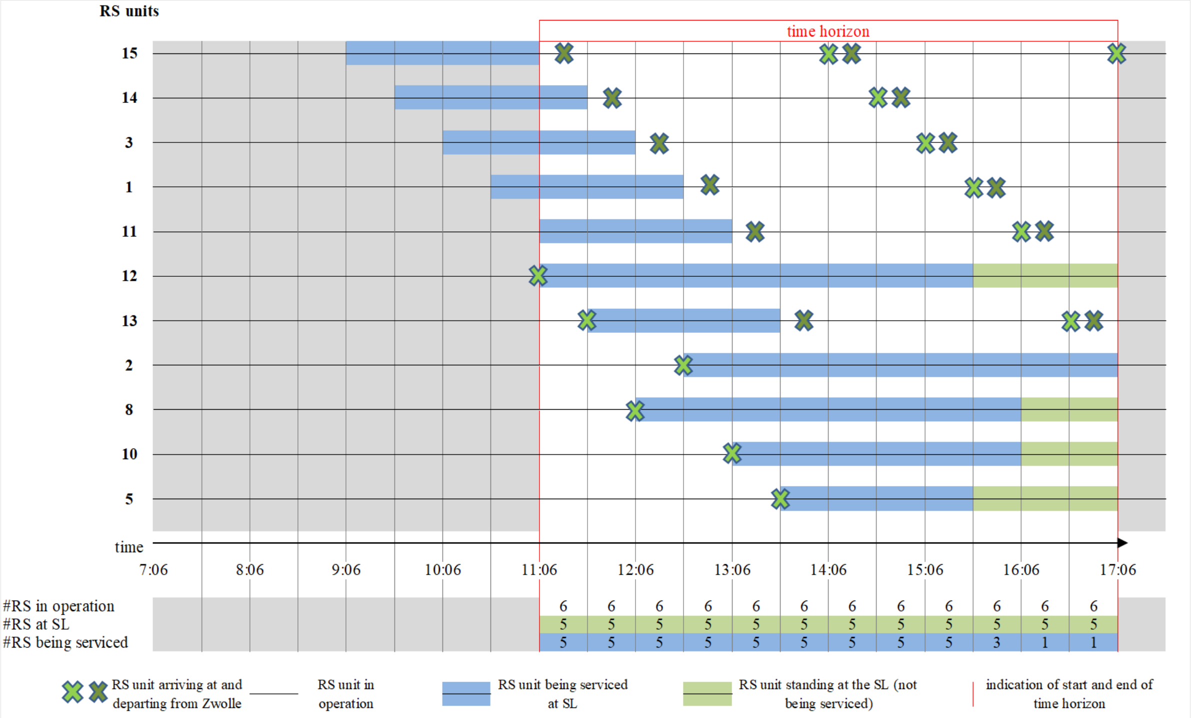


Figure 5.3: RS movements – Base Scenario applied to the RS-SSP Base Model

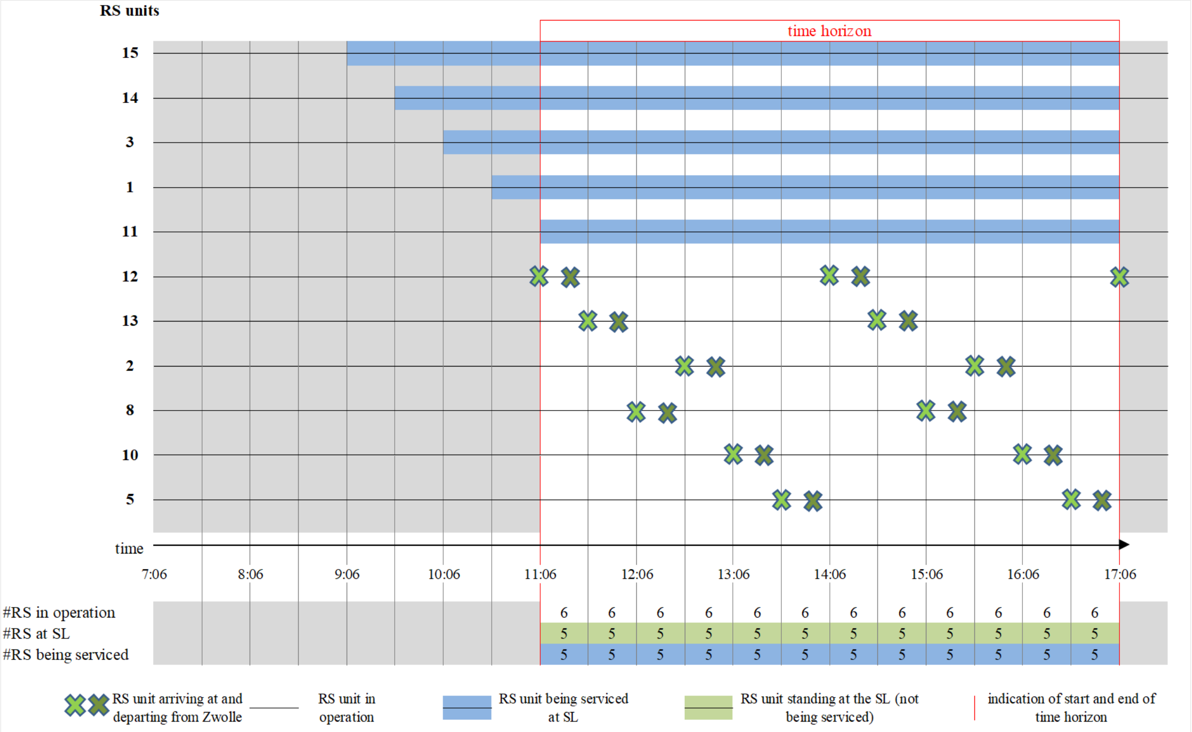


Figure 5.4: RS movements – Scenario 11 applied to the RS-SSP Base Model

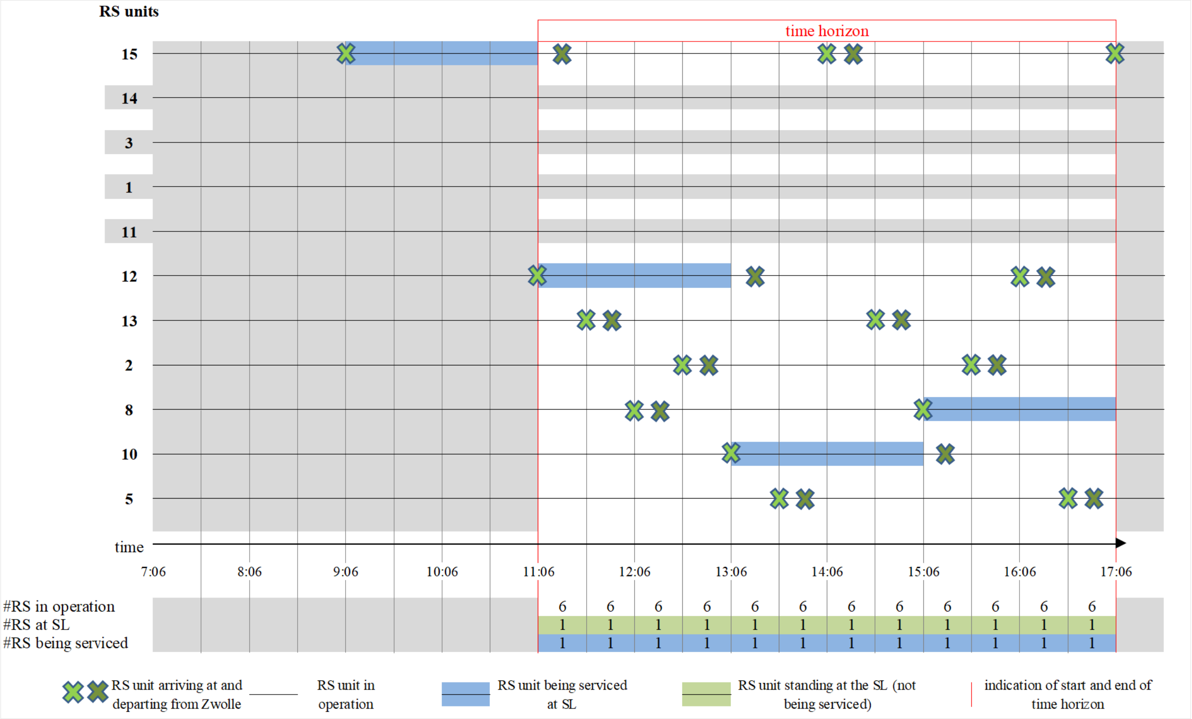


Figure 5.5: RS movements – Scenario 15 applied to the RS-SSP Base Model

5.1.3. The Impact of Parameter Changes

In this section, the results given in the previous Section are further analysed and the impact of parameter changes is brought into focus. First, the impact of a single parameter change is observed. In a second step, the impact of a combinatorial parameter change is examined. While Table 5.5 presents important measures of the single parameter changes, Table 5.6 entails information about the combinatorial parameter changes.

In the first column of Table 5.5 six input parameters are listed as they are examined with respect to changing values. The second column entails the divers values used for the changing parameter. The third column gives the resulting values of the objective function (OF) for the Base Scenario, with the value of the changing parameter being adapted accordingly. The fourth column (#RS) indicates the total number of RS units being used for the corresponding scenario. Then, the sixth column (OF/#RS) shows the percentage of RS numbers being serviced in relation to the total number of used RS units. This ratio can also be called servicing rate. Finally, the last column provides additional comments, where necessary.

While the objective function provides exact numbers of RS units being serviced, the servicing rate can indicate whether all used RS units can complete servicing or only part of them. In case the percentage is 100% all used RS units can complete servicing. A percentage lower than 100% indicates how many RS units of the total number of used RS units are considered.

As can be seen in Table 5.5 most of all used RS units can complete servicing when changing only a single parameter (i.e. 100% servicing rate). Of course, this is not the case for infeasible solutions (i.e. $SL^{max} \leq SL_0$). Note that for values of SL_0 larger than 5, SL^{max} is set equally to SL_0 in order to yield feasible solutions (see comment). For SL_0 smaller or equal to 2, it is not possible to let all RS units complete servicing. As $tt_k \leq tt_{min}$ implies that RS units cannot be exchanged, only the RS units standing initially at the SL can be serviced. Moreover, a servicing duration of 3 hours as well as a train arrival frequency of every 15 minutes do not allow all used RS units to be serviced.

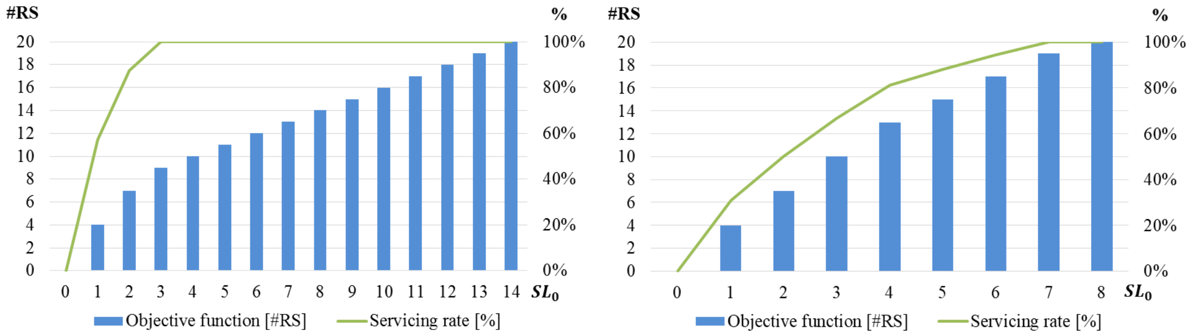
Changing Parameter	Parameter Value	OF	#RS	OF/#RS	Comment
SL_0	1	4	7	57%	
	2	7	8	88%	
	3	9	9	100%	
	4	10	10	100%	
	5	11	11	100%	
	6	12	12	100%	$SL^{max} = 6$
	14	20	20	100%	$SL^{max} = 14$
tt_k	$\geq tt^{min}$	11	11	100%	
	$< tt^{min}$	5	11	45%	no RS exchange
tt^{min}	$\leq tt_k$	11	11	100%	
	$> tt_k$	5	11	45%	no RS exchange
SL^{max}	$\geq SL_0$	11	11	100%	
	$< SL_0$	infeasible	11	-	infeasible
d^{max}	00:30	11	11	100%	
	01:00	11	11	100%	
	02:00	11	11	100%	
	03:00	10	11	91%	
headway	15	15	17	88%	
	30	11	11	100%	
	60	8	8	100%	

Table 5.5: Single parameter changes

In Table 5.6, the impact of SL_0 is further analysed. Here, the headway is set to 15 minutes as opposed to the 30 minutes used for the Base Scenario. It can be seen that for the higher train arrival frequency, larger values are required for SL_0 in order to obtain a 100% servicing rate. This is also visualised in Figure 5.6.

Changing Parameter	Parameter Value	OF	#RS	OF/#RS
SL_0	1	4	13	31%
	2	7	14	50%
	3	10	15	67%
	4	13	16	81%
	5	15	17	88%
	6	17	18	94%
	7	19	19	100%
	8	20	20	100%

Table 5.6: Impact of SL_0 with a headway of 15 minutes



(a) Impact of SL_0 with a headway of 30 minutes

(b) Impact of SL_0 with a headway of 15 minutes

Figure 5.6: Impact of parameter changes of SL_0

To sum up, the parameter changes of SL_0 and the headway both imply changes in the total number of available RS units ($\#RS$). As can be seen in Table 5.5, the resulting values of the objective function are strongly affected by these changes. Regarding the servicing rate, however, the changes are by far less grave. This has to do with the tightness of the restrictions. The tighter the limitations, the lower becomes the servicing rate. This also applies to individual changes of the servicing (and shunting) duration (d^{max}). Regarding adaptations of the minimum turning time (tt^{min}) or the maximum allowed number of RS units being serviced (SL^{max}), there are critical values. Parameter values which do not exceed the critical value are not binding meaning that they do not present any limitations to the model. Exceeding the critical value, however, leads to no RS exchange (i.e. $tt^{min} \geq tt_k$) or infeasibility (i.e. ($SL^{max} \leq SL_0$). While tt_k and tt^{min} represent each other's critical value, the critical value of SL^{max} is SL_0.

The combination in parameter changes of the headway and SL_0 has even larger impact on the outcome than individual parameter changes. This is due to the fact that setting the headway to 15 minutes tightens the restrictions of the model. Therefore, only values of SL_0 higher or equal to 7 lead to a hundred percent servicing rate. Remember that with a headway of 30 minutes, the hundred percent servicing rate could be reached already with $SL_0 = 3$. These differences are visualised in Figure 5.6.

5.2. Model Comparison

After experimenting with the Base Model, relevant scenarios have been selected in order to calibrate and validate the RS-SSP extensions. While Section 5.2.1 defines the selected scenarios, Section 5.2.2 provides the results per scenario applied to each model. By means of the results, the three models are compared to one another. Finally, Section 5.2.3 provides an overview about the impact of individual and combinations of parameter changes on the results for each model.

5.2.1. Definition of Scenarios

One crucial advantage of the RS-SSP extensions (i.e. RS-SSP-MU and RS-SSP-MU-W) is the possibility of extending the time horizon. Instead of starting at 11:06, when the first RS unit can be exchanged according to the BDU plan, the RS-SSP extensions can be applied to a time horizon starting at 07:06, when the first train arrives at Zwolle station. The reason for this is that the RS-SSP-MU models can handle trains running with multiple RS units and also allow RS units to enter the SL without enforcing an RS exchange. Remember that the RS-SSP Base Model only allows RS exchanges and thus RS units would need to be initially at the SL in order to enable operating RS units to enter the SL.

Moreover, the RS-SSP Base Model assumes that all trains run with a length of one RS unit. According to the BDU plan, however, trains departing from Zwolle station between 14:53 and 16:23 run with a length of two RS units (see Table 4.1). This means that the trains arriving in the same phase running with only one RS unit need to be coupled with an additional RS unit. These additional RS units are currently the ones standing on reserve at the SL. Regarding the RS exchange concept, it might be possible that all RS units at the SL are being serviced. The RS-SSP-MU models, however, ensure that the BDU plan is met as trains running with multiple RS units are taken into account. Therefore, there are always sufficient RS units ready for operation as stated by the BDU plan. As a consequence, the RS-SSP extensions can perfectly handle a time horizon ending at 17:23 with the last departing train before the start of the evening peak. The time horizon applied to the Base Model, in contrast, only covers the off-peak period lasting until 14:23, in which all arriving and departing trains run with a length of one RS unit. The timetable as provided by the BDU plan is visualised in Figure 5.7, whereby double arrows stand for trains running with two RS units and single arrows for single-RS-unit-trains. The different time horizons considered by the model extensions (i.e. RS-SSP-MU and RS-SSP-W) and the RS-SSP Base Model are indicated on the right side of the figure.

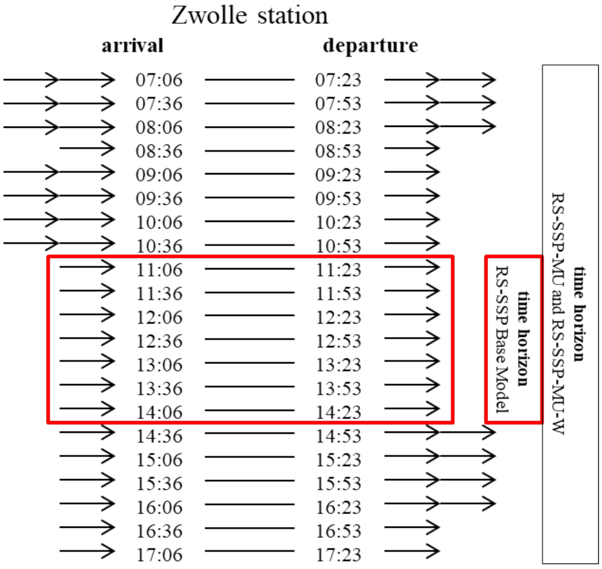


Figure 5.7: Timetable of the Base Scenario according to the BDU plan

The parameter values of the Base Scenario as described in Table 5.1 need to be slightly adapted in order to apply the same scenario to the RS-SSP extensions. This is based on the extended time horizon applied to the RS-SSP-MU models. Remember that the Base Scenario as described in Table 5.1 has a time horizon starting at 11:06. Therefore, RS units standing initially at the SL need to be manually fixed (e.g. $SL_0 = 5$ for the Base Scenario). At 07:06, however, all used RS units are in operation, so no RS units are standing at the SL (i.e. $SL_0 = 0$). From 09:06 RS units automatically roll out towards the SL as the train lengths of the departing trains are shorter than of the trains arriving in the same phase. $SL_0 = 0$ in the RS-SSP extensions having a time horizon starting at 07:06, thus, means exactly the same as $SL_0 = 5$ in the Base Model having a time horizon starting at 11:06. In both cases, 5 RS units are standing at the SL at 11:06. It should be noted that despite the train length of two RS units, the time horizon of the RS-SSP Base Model can start at 11:06. This is possible because one of the two RS units running with the train arriving at 11:06 can be covered by the RS units standing initially at the SL having an entering time (T^{in}) of 11:06).

The scenarios applied to the RS-SSP extensions were selected on behalf of relevance and interest. By means of the previous experiments with the Base Model, multiple scenarios could be rejected based on irrelevance. Changing the turning time (tt_k) or adapting the minimum required turning time (tt^{min}), for instance, seemed irrelevant due to obvious outcomes. As soon as $tt_k \geq tt^{min}$, no limitations are given by tt^{min}. In case $tt_k < tt^{min}$ for all trains k, no RS exchange is possible and the outcome of the objective function equals the number of RS units automatically rolling out towards the SL (e.g. 5 RS units in the Base Scenario).

Table 5.7 lists all scenarios applied to the RS-SSP Base Model, RS-SSP-MU, and RS-SSP-MU-W. As can be seen in Table 5.7, tt_k and tt^{min} remain consistently on 17 and 10 minutes respectively and thereby do not present any limitations. The headway is mostly kept at 30 minutes, only the last 4 scenarios test higher frequencies with a headway of 15 minutes. Note that the different values for the total number of RS units ($\#RS$) are not explicitly selected yet result by changing the frequency. With a headway of 30 minutes as prescribed by the BDU plan 11 RS units are used. Doubling the frequency means doubling the number of trains and thus also implies doubling the total number of RS units being used.

The experiments as described in the scenarios of Table 5.7 mainly focus on different values for d^{max} and SL^{max}. Especially for the RS-SSP-MU-W model, changing values of SL^{max} becomes very interesting as the RS-SSP-MU-W model can cope with RS units waiting for being serviced. Note that when SL^{max} is lower than the total number of RS units rolling out towards the SL (5 RS units for the Base Scenario), the RS-SSP Base Model and the RS-SSP-MU model deliver infeasible solutions. This is due to their model assumption of servicing RS units immediately when entering the SL. The functionality of the RS-SSP-MU-W model allowing RS units to wait at the SL for being serviced may, of course, also impact the total duration of an RS unit standing at the SL. Experimenting with SL^{max} in combination with d^{max}, thus, seemed to be interesting.

Scenario	**headway**	$\#RS$	SL_0 [10]	tt_k	tt^{min}	d^{max}	SL^{max}
Base Scenario	30	11	0	00:17	00:10	02:00	5
Scenario 2	30	11	0	00:17	00:10	02:00	4
Scenario 3	30	11	0	00:17	00:10	02:00	3
Scenario 4	30	11	0	00:17	00:10	02:00	2
Scenario 5	30	11	0	00:17	00:10	02:00	1
Scenario 6	30	11	0	00:17	00:10	01:00	1
Scenario 7	30	11	0	00:17	00:10	00:30	1
Scenario 8	30	11	0	00:17	00:10	03:00	≥ 5
Scenario 9	30	11	0	00:17	00:10	03:00	4
Scenario 10	30	11	0	00:17	00:10	03:00	3
Scenario 11	30	11	0	00:17	00:10	03:00	2
Scenario 12	30	11	0	00:17	00:10	03:00	1
Scenario 13	15	22	0	00:17	00:10	02:00	10
Scenario 14	15	22	0	00:17	00:10	03:00	10
Scenario 15	15	22	0	00:17	00:10	01:00	10
Scenario 16	15	22	0	00:17	00:10	00:30	10

Table 5.7: Scenarios applied to the RS-SSP extensions

5.2.2. Model Results per Scenario

In this section the outcomes of the three models (i.e. RS-SSP Base Model, RS-SSP-MU, and RS-SSP-MU-W) are compared to one another. Table 5.8 provides an overview of the results per scenario for each model. Similar to Table 5.4, multiple measures were taken into account in order to achieve more details of the solutions. Beside the measures listed in Table 5.4, Table 5.8 also entails the calculation times per scenario. As opposed to the Base Model experiments in Section 5.1, where the calculation time never exceeded 1 second, the calculation time of the RS-SSP-MU-W increases drastically when applying the model to certain scenarios. Therefore, the calculation time was added as measure.

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[10] Note that for the RS-SSP Base Model $SL_0 = 5$

Scenario	**Measures**	**RS-SSP** [11]	**RS-SSP-MU**	**RS-SSP-MU-W**
Base Scenario	Objective function	8	11	11
	avg #RS at SL	5.0	2.8	2.8
	avg #RS being serviced	5.0	2.2	2.4
	avg duration at SL	2:30	2:32	2:32
	avg servicing duration	2:30	2:00	2:05
	Calculation time	< 1s	< 1s	< 1s
Scenario 2	Objective function	infeasible	infeasible	11
	avg #RS at SL			2.8
	avg #RS being serviced			2.4
	avg duration at SL			2:32
	avg servicing duration			2:05
	Calculation time	< 1s	< 1s	< 1s
Scenario 3	Objective function	infeasible	infeasible	10
	avg #RS at SL			2.8
	avg #RS being serviced			2.0
	avg duration at SL			2:5
	avg servicing duration			2:00
	Calculation time	< 1s	< 1s	< 1s
Scenario 4	Objective function	infeasible	infeasible	7
	avg #RS at SL			2.8
	avg #RS being serviced			1.5
	avg duration at SL			4:00
	avg servicing duration			2:04
	Calculation time	< 1s	< 1s	73s
Scenario 5	Objective function	infeasible	infeasible	infeasible
	Calculation time	< 1s	< 1s	25s
Scenario 6	Objective function	infeasible	infeasible	8
	avg #RS at SL			2.8
	avg #RS being serviced			2.0
	avg duration at SL			3:33
	avg servicing duration			1:00
	Calculation time	< 1s	< 1s	5461s
Scenario 7	Objective function	infeasible	infeasible	11
	avg #RS at SL			2.8
	avg #RS being serviced			0.7
	avg duration at SL			2:32
	avg servicing duration			0:35
	Calculation time	< 1s	< 1s	1s
Scenario 8	Objective function	5	9	9
	avg #RS at SL	5.0	2.8	2.8
	avg #RS being serviced	3.3	2.7	2.7
	avg duration at SL	3:00	3:06	3:06
	avg servicing duration	3:00	3:00	3:00
	Calculation time	< 1s	< 1s	1s
Scenario 9	Objective function	infeasible	infeasible	8
	avg #RS at SL			2.8
	avg #RS being serviced			2.4
	avg duration at SL			3:30
	avg servicing duration			3:00
	Calculation time	< 1s	< 1s	1s
Scenario 10	Objective function	infeasible	infeasible	6
	avg #RS at SL			2.8
	avg #RS being serviced			1.9
	avg duration at SL			4:40
	avg servicing duration			3:10
	Calculation time	< 1s	< 1s	1s

Scenario	Measures	RS-SSP [11]	RS-SSP-MU	RS-SSP-MU-W
Scenario 11	Objective function	infeasible	infeasible	4
	avg #RS at SL			2.8
	avg #RS being serviced			1.2
	avg duration at SL			5:36
	avg servicing duration			2:24
	Calculation time	< 1s	< 1s	7s
Scenario 12	Objective function	infeasible	infeasible	infeasible
	Calculation time	< 1s	< 1s	< 1s
Scenario 13	Objective function	14 [12]	22	22
	avg #RS at SL	10.0	5.7	5.7
	avg #RS being serviced	6.4	4.9	4.9
	avg duration at SL	2:46	2:35	2:35
	avg servicing duration	2:03	2:16	2:14
	Calculation time	< 1s	< 1s	8s
Scenario 14	Objective function	9 [12]	18	18
	avg #RS at SL	10.0	5.7	5.7
	avg #RS being serviced	7.2	5.5	5.5
	avg duration at SL	3:52	3:09	3:09
	avg servicing duration	3:06	3:04	3:04
	Calculation time	< 1s	2s	25s
Scenario 15	Objective function	18 [12]	22	22
	avg #RS at SL	10.0	5.7	5.7
	avg #RS being serviced	8.1	2.8	3.5
	avg duration at SL	2:09	2:39	2:39
	avg servicing duration	1:53	1:15	1:36
	Calculation time	< 1s	< 1s	1s
Scenario 16	Objective function	20 [12]	22	22
	avg #RS at SL	10.0	5.7	5.7
	avg #RS being serviced	8.6	1.7	1.8
	avg duration at SL	2:00	2:32	2:32
	avg servicing duration	1:45	0:47	0:49
	Calculation time	< 1s	< 1s	1s

Table 5.8: Model Comparison

As visualised in Table 5.8, a large number of scenarios applied to the RS-SSP Base Model and the RS-SSP-MU model deliver infeasible solutions. This outcome is in accordance with the expectations as those scenarios entail values for SL^{max} lower than 5, which is the number of RS units rolling out towards the SL before 11:06. The RS-SSP-MU-W can mostly handle the low values for SL^{max}. However, the solutions for Scenarios 5 and 12 are also infeasible. This means that for servicing durations longer or equal to two hours, no solution exists in case only one RS unit can be serviced per moment in time ($SL^{max} = 1$). As all of the models oblige RS units to complete servicing before leaving the SL, there are not sufficient RS units available for operations as dictated by the BDU plan. Remember that for trains departing from 14:53 RS units standing at the SL are required to operate as the trains departing from 14:53 run with a length of two RS units. In Scenario 5, the servicing time is 2 hours and the maximum number of RS units being serviced simultaneously is one. The first RS unit rolling out towards the SL at 09:06 could complete servicing at 11:06, so the second RS unit could start being serviced at 11:06. The second RS unit could thus complete servicing at 13:06, the third again two hours later at 15:06, the fourth RS unit at 17:06, and so on. While the first two RS units could complete servicing in time to operate the trains departing at 14:53 and 15:23, the third RS unit would not be ready to operate in the train departing at 15:53 (and the forth would not be ready for the train departing at 16:23). Therefore, the timetable could not be met as given by the BDU plan and the model is infeasible.

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[11] Note that the time horizon of the Base Model only lasts from 11:06 to 14:23.

[12] Note that the time horizon of the Base Model only lasts from 11:21 to 14:23 when doubling the train arrival frequency because the last RS unit rolling out towards the SL after the morning peak enters the SL at 11:21.

Moreover, the servicing duration plays an important role with respect to the model outcomes. Scenarios 6 and 7, for instance, also set SL^{max} to 1 yet assume lower servicing durations as opposed to Scenario 5. While Scenario 5 led to an infeasible model, Scenarios 6 and 7 achieve objective functions with values of 8 and 11 RS units having completed servicing. Obviously, the shorter the servicing (and shunting) duration (d^{max}), the more RS units can complete servicing. Similarly, the larger the maximum allowed number of RS units being serviced simultaneously (SL^{max}), the better the results of the objective function. Note that the objective function never exceeds the total number of used RS units (# RS). When achieving the maximum possible value of the objective function already for higher d^{max} or lower SL^{max}, the value of the objective function cannot increase for lower d^{max} or higher SL^{max}. For this reason, the objective function of the Base Scenario, Scenario 2, and Scenario 7 are exactly the same when applying to the RS-SSP-MU-W.

It is observable that the outcomes of the RS-SSP-MU are very similar to the RS-SSP-MU-W in case of a feasible solution. The outcomes of the RS-SSP Base Model, in contrast, significantly distinguish from the extended models. This is very obvious when looking into the outcomes of the objective function. The objective function of the two extended models is always the same in case of a feasible solution, whereas the Base Model never delivers equal objective function values compared to the other two models. The same is also true for the average number of RS units standing at the SL. While the results of this measure are for the Base Model integer values as explained in Section 5.1.2, the values for the RS-SSP-MU and RS-SSP-MU-W can be decimal. The reason for the decimal solution is the varying number of RS units standing at the SL in time – During the morning peak no RS units stand at the SL and during the off-peak hours up to 5 RS units stand at the SL.

It is important to understand that the outcomes of the RS-SSP Base Model are not directly comparable with those of the two extended model versions due to the different considered time horizons. Obviously, the total number of RS units being able to complete servicing is lower in case of a shorter period of time. The shorter time horizon can thus be seen as an additional restriction to the model. Note that for the first twelve scenarios with a headway of 30 minutes the time horizon of the Base Model starts at 11:06, whereas the time horizon of the last four scenarios having a 15 minutes headway starts at 11:21. This is based on the missing functionality of the Base Model of coping with trains running with multiple RS units. In the scenarios with a doubled train arrival frequency, the last train arriving after the morning peak with a length of two RS units arrives at 11:21 (instead of at 11:06, as it is the case for the 30 minutes headway scenarios).

Due to the fixed timetable, the average number of RS units standing at the SL is steady for a constant total number of used RS units. The first twelve scenarios, for instance, assume a usage of 11 RS units (i.e. $\#RS = 11$) resulting in an average number of 5 and 2.8 RS units standing at the SL when applied to the RS-SSP Base Model and the model extensions, respectively. Note that also the original BDU plan leads to an average number of 2.8 RS units standing at the SL (see Table 5.4). For the last scenarios assuming a doubled number of used RS units (i.e. 22 RS units), the average number of RS units standing at the SL is with 10 for the Base Model exactly doubled and with 5.7 for the extended models almost doubled as compared to the previous scenarios. This doubling is based on the doubled train arrival frequency leading to a doubled number of operating RS units and a doubled number of RS units rolling out towards the SL. The inaccuracy of the *almost* doubled value of 5.7 instead of an exact doubled value of 5.8 for the average number of RS units standing at the SL according to the extended model versions can be explained by the time horizon starting at 07:06 and ending at 17:06. Doubling the train arrival frequency leads almost yet not exactly to a doubled total number of trains arriving at and departing from Zwolle when considering the time horizon from 07:06 until 17:06. This is because the train arriving at 17:21 is not taken into account.

The average number of RS units being serviced as well as the average servicing duration can vary between the two extended models even if the values of their objective function are equal. This can be explained by the possibility of the models to increase the servicing durations with respect to the minimum required servicing duration. As mentioned in 5.1.2, the additional servicing duration considered by the models can be treated as buffer times. Certainly, these varying average values might be indicators of servicing efficiency – the lower the buffer time, the shorter the servicing duration. However, as the models do not try to maximise the servicing duration, the outcome of the average servicing duration may in the one case include the buffer time and in the other exclude the buffer time. Therefore, the comparison of the average servicing durations may not lead to a meaningful analysis. It is worth mentioning that the average number of RS units being serviced is influenced by the average servicing duration. In general, a longer servicing duration leads to more RS units being serviced per moment in time in case the total number of RS units being serviced does not change.

Mostly, the average servicing duration of the RS units standing at the SL is larger than the minimum required servicing duration due to the additional buffer time. A lack in buffer time leads to average servicing durations equal to the minimum servicing durations of Scenarios 6, 8, and 9. Scenario 11, however, features an even lower average servicing duration (i.e. 2:24) than the minimum required servicing duration (i.e. 3:00). This might seem odd at first yet can be explained. The reason for this is the lower number of RS units being serviced (i.e. 4 RS units according to the objective function) as compared to the number of RS units standing at the SL (i.e. 5 RS units according to the BDU plan). As the average servicing duration considers all RS units visiting the SL, the servicing duration of zero minutes for the one RS unit not being serviced significantly decreases the average servicing duration. The reason for not cleaning all RS units standing at the SL is the lack in time. It should be mentioned here that as long as the RS units do not need to operate, the model is not forcing them to be serviced.

Regarding the calculation times, the RS-SSP-MU model shows more similarities to the RS-SSP Base Model than to the RS-SSP-MU-W. While all calculation times of the Base Model are lower than one second, the RS-SSP-MU model features one exception in Scenario 14, which takes two seconds. The RS-SSP-MU-W model, in contrast, shows frequently longer calculation times. Outstanding, however, is only one scenario. The application of Scenario 6 to the RS-SSP-MU-W model has a calculation time of 5461 seconds, whereas all other experiments feature calculation times lower than 74 seconds. It seems as if the RS-SSP-MU-w model has difficulties to find the optimal solution. In case of a feasible model, tighter restrictions may increase the calculation time. This can also be observed at Scenario 4, which features a significantly higher calculation time as opposed to the other scenarios (aside of Scenario 6). However, Scenario 11, for instance, shows a very low calculation time even though its restrictions are very tight (leading to only 4 RS units being able to complete servicing). It is worth mentioning that when running a certain scenario multiple times, the calculation time may vary. It is thus possible that the model finds the optimal solution sometimes faster than in other instances.

In the following, the scenarios, which lead to feasible solutions for all models, are visualised and further analysed. Figures 5.8 to 5.13 visualise the RS movements of the achieved optimal solutions of the Base Scenario and Scenario 8 as applied to each of the three models. Furthermore, Figure B.4 shows the RS movements for doubled arrival frequencies according to Scenarios 13 and 14.

As can be seen in Figures 5.8 to 5.13, the arrival (and departure) times at Zwolle per RS unit as marked by the light (and dark) green crosses are initially the same for all three models as the first train arrivals are given as input parameters to the models. From the moment that RS units enter the SL, however, the RS circulation may change. Furthermore, it becomes visual that not only RS exchanges are allowed to the extended models, as in the case for the RS-SSP Base Model, but that RS units can also visit and leave the SL without being substituted by another RS unit. Therefore, the number of operating RS units and RS units standing at the SL can change in time according to the BDU plan. The time horizon of the Base Model only considers the time period in which these numbers stay constant.

The total number of RS units being serviced can be calculated by summing up the total number of blue bars. This number equals the objective function as given in Table 5.8. Rows without a blue bar indicate RS units, which are not being serviced within the considered time horizon. Note that the RS-SSP-MU and the RS-SSP-MU-W model feature a time horizon covering the entire period of potential daytime servicing. The Base Model, in contrast, incorporates a very limited time interval.

Comparing the RS movements of the two extended model versions to each other shows higher differences than comparing the model outcomes with respect to the six measures of Table 5.8. This difference is based on the diversity of detail. While the measures given in Table 5.8 mainly indicate average values, the RS movements visualised in Figures 5.8 to 5.13 provide a substantial amount of information on RS unit level. It should be noted that differences in RS movements can vary when running an application multiple times. The decision which of the two RS units arriving in the same train at Zwolle rolls out towards the SL at 09:06, for instance, can vary each time when running the model application. In the Base Model, however, the RS units rolling out towards the SL are fixed by the set RS^{SL_0}.

An important difference between the RS-SSP-MU and the RS-SSP-MU-W, however, is the appearance of green bars on the left-side of blue bars. These left-sided green bars indicate the waiting time until being serviced. This is the main additional function of the RS-SSP-MU-W compared to the RS-SSP-MU. This functionality led to the feasibility of multiple scenarios being infeasible for the RS-SSP-MU as can be seen in Table 5.8. However, it did not lead to increasing objective functions for feasible solutions of the RS-SSP-MU.

The longer servicing duration of Scenario 8 leads to lower appearances of RS units standing at the SL without being serviced (green bars) for the RS-SSP-MU and the RS-SSP-MU-W model. This is due to the lower buffer time leading to higher time efficiency. The solutions yielded by the Base Model, in contrast, indicate higher appearances of RS units standing at the SL without being serviced. This is because the servicing durations given by the optimal solution for the Base Scenario include buffer time, whereas the servicing durations in Figure B.1 equal the minimum required servicing duration of three hours for all RS units being serviced. Aggregating the buffer time included in the servicing duration in the Base Scenario leads to exactly the same amount of the cumulated time period of RS units standing at the SL without being serviced as resulting from Scenario 8.

As opposed to the experiments conducted in Chapter 5.1.2, the RS circulation after the considered time horizon does comply with the original BDU plan. Certainly, the specific RS units may vary from the original plan due to different RS units standing at the SL at the end of the considered time horizon. However, the number of operating RS units as resulting from the models equal that of the original plan. This is due to considering the planned timetable. Remember that in Chapter 5.1.2, the timetable was adapted with respect to the number of RS units running per train.

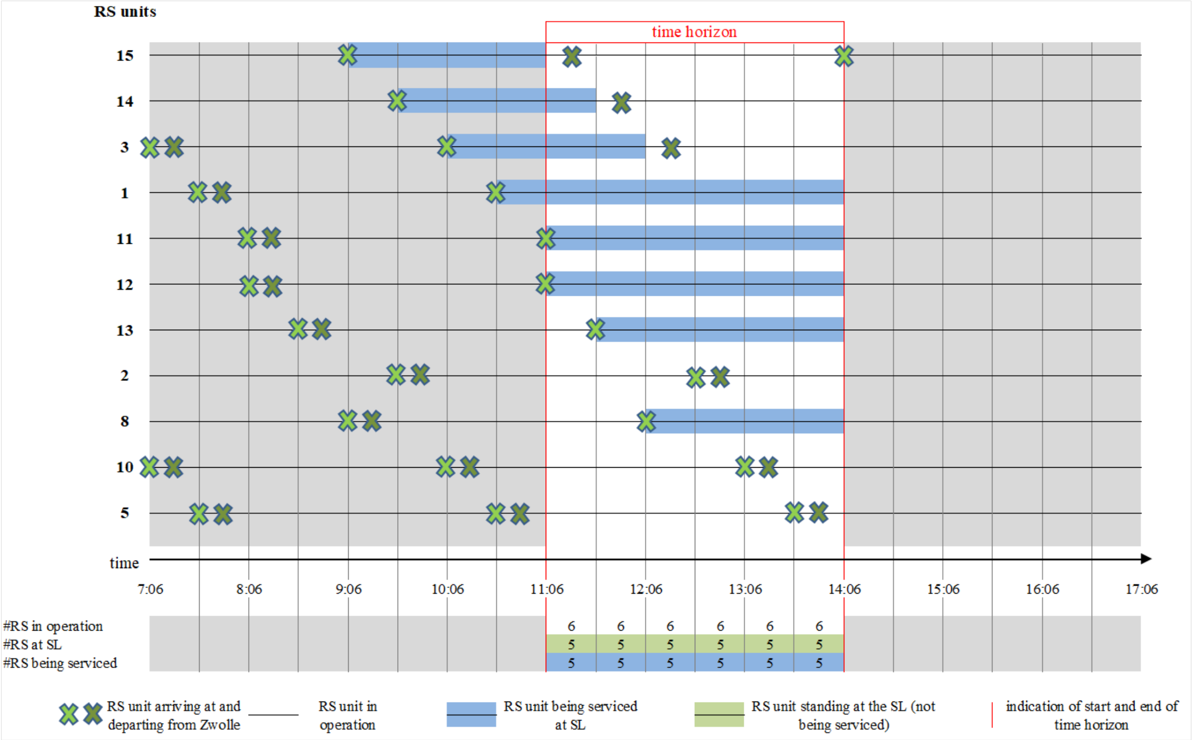


Figure 5.8: Base Scenario applied to the RS-SSP Base Model

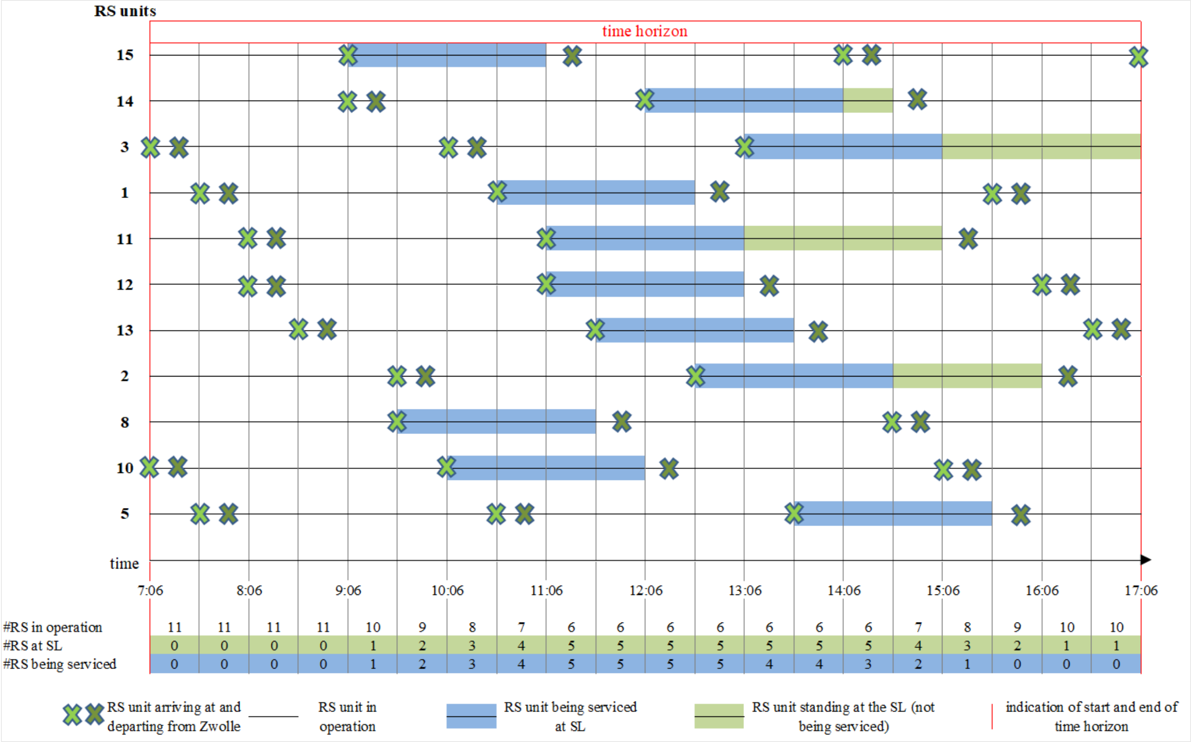


Figure 5.9: Base Scenario applied to the RS-SSP-MU

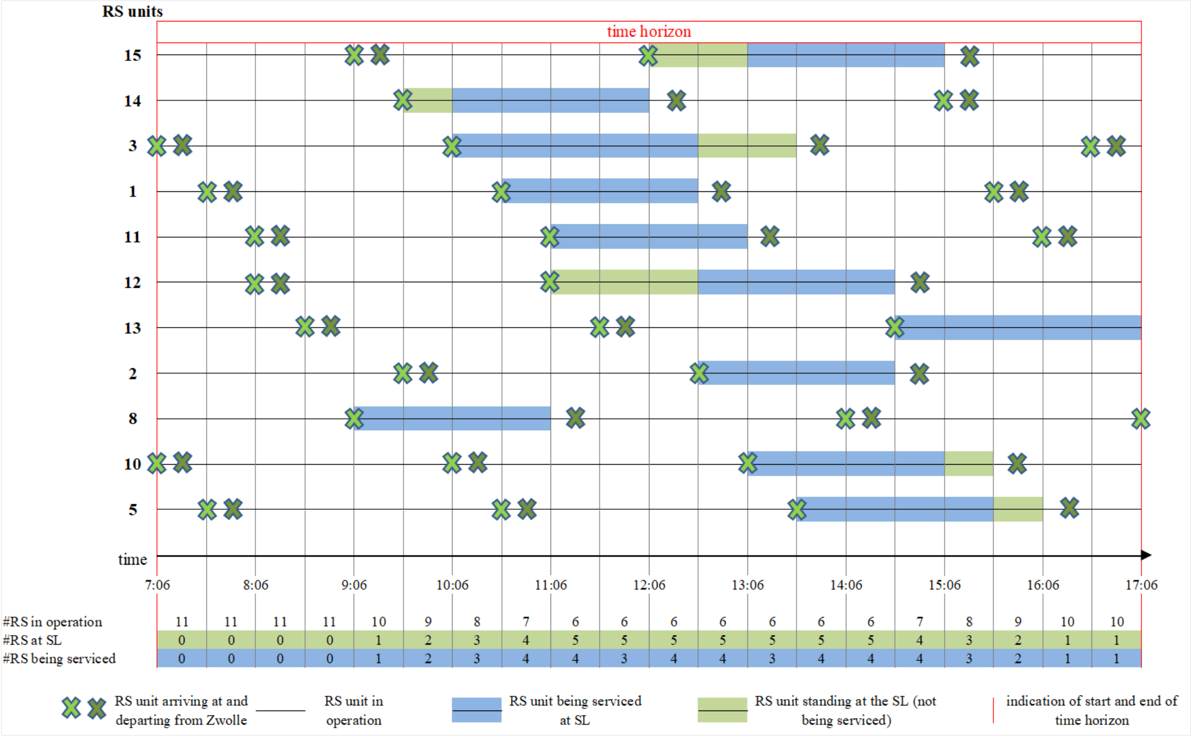


Figure 5.10: Base Scenario applied to the RS-SSP-MU-W

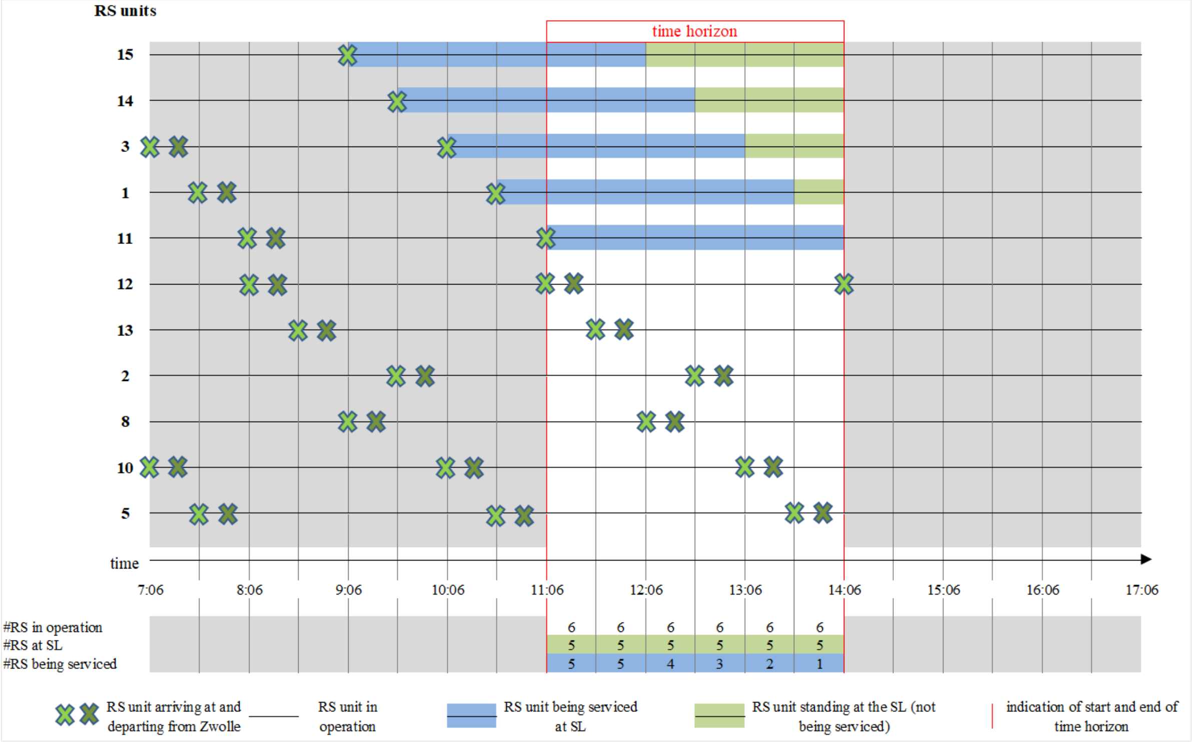


Figure 5.11: Scenario 8 applied to the RS-SSP Base Model

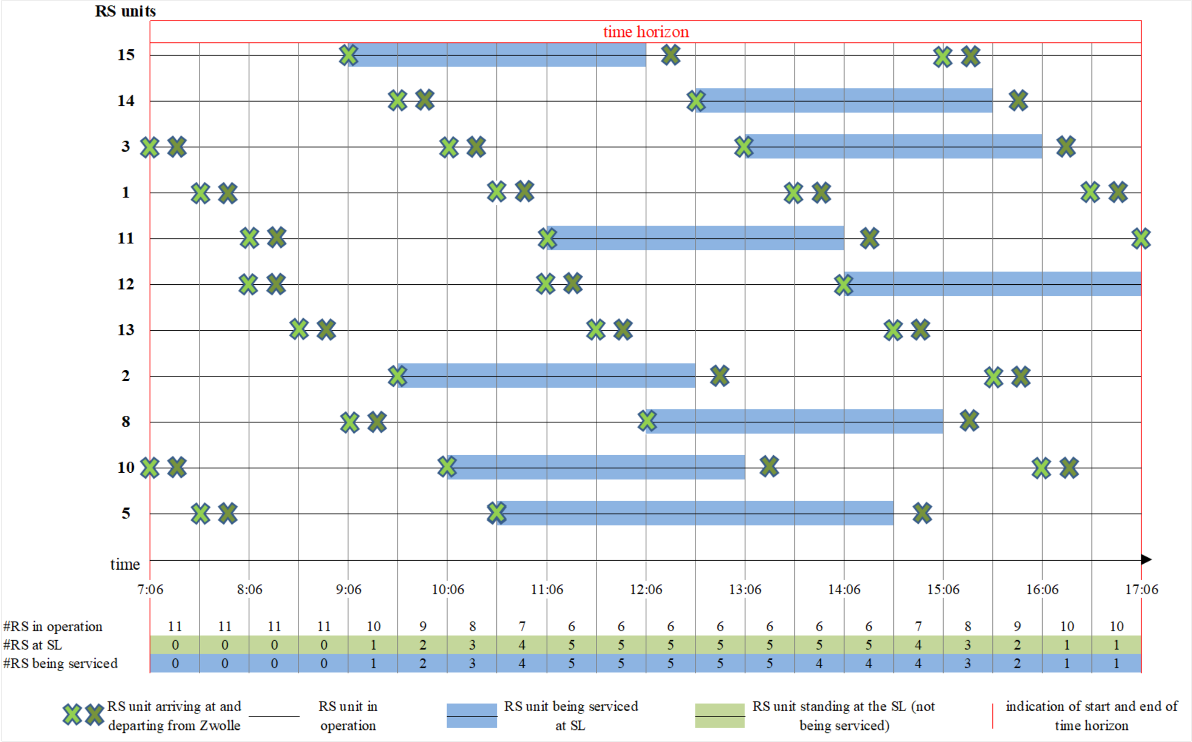
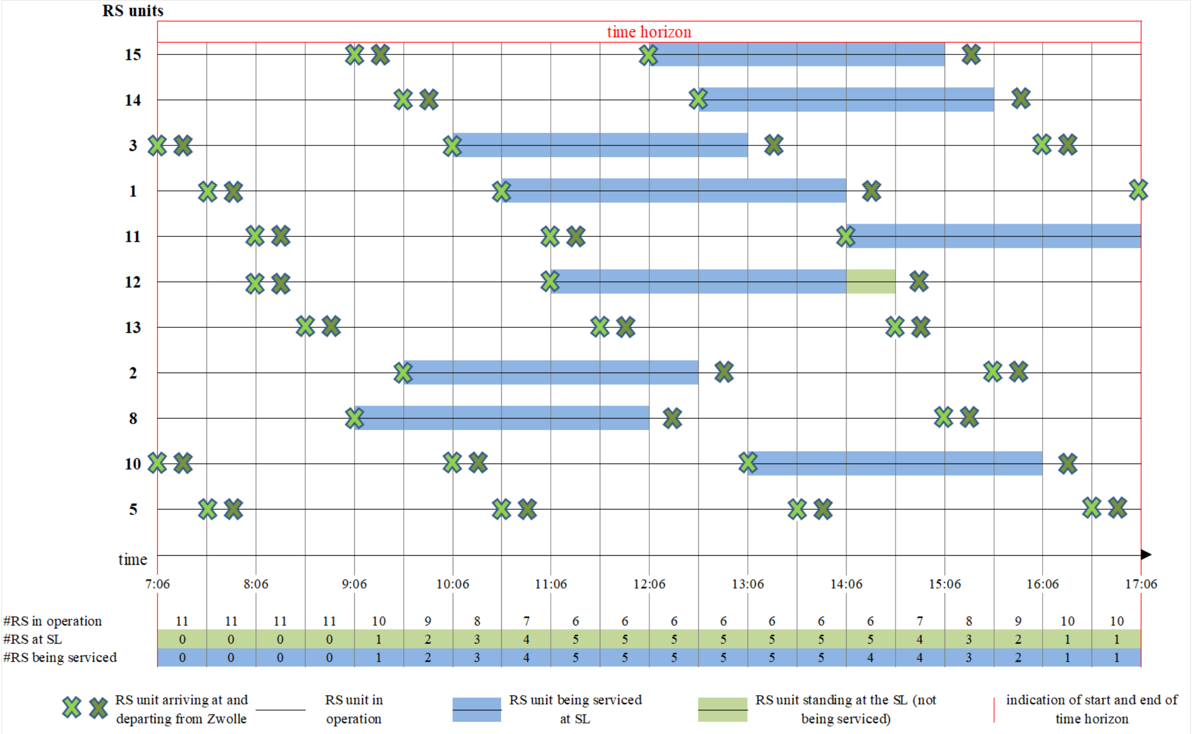


Figure 5.12: Scenario 8 applied to the RS-SSP-MU



#RS in operation	11	11	11	11	10	9	8	7	6	6	6	6	6	6	6	7	8	9	10	10
#RS at SL	0	0	0	0	1	2	3	4	5	5	5	5	5	5	5	4	3	2	1	1
#RS being serviced	0	0	0	0	1	2	3	4	5	5	5	5	5	5	4	4	3	2	1	1

Figure 5.13: Scenario 8 applied to the RS-SSP-MU-W

5.2.3. The Impact of Parameter Changes

This Section helps to clearly see the impact of parameter changes on the results of the three different models. Table 5.9 presents a comparison of the three models based on a single parameter change. The scenarios described in Table 5.9 take the Base Scenario as basis, with one parameter being changed.

Changing Parameter	**Parameter Value**	**Objective Function**		
		RS-SSP	**RS-SSP-MU**	**RS-SSP-MU-W**
SL^{max}	1	infeasible	infeasible	infeasible
	2	infeasible	infeasible	7
	3	infeasible	infeasible	10
	4	infeasible	infeasible	11
	5	8	11	11
d^{max}	00:30	11	11	11
	01:00	10	11	11
	02:00	8	11	11
	03:00	5	9	9

Table 5.9: Single Parameter Changes

Note that the number of available RS units ($\#RS$) is 11 for all scenarios described in Table 5.9. Therefore, the servicing rate is directly related to the objective function values. The servicing rate is not indicated here as it does not present additional value compared to the objective function (see Figure 5.14). The outcomes of the objective function can directly be compared to one another due to the constant value of the total number of available RS units.

Table 5.10 lists the outcomes of the objective function per model for combinatorial parameter changes. Firstly, d^{max} is set to three hours. While all models lead to an infeasible solution for $SL^{max} = 1$, the RS-SSP-MU-W model provides solutions for values of SL^{max} larger than 1. $SL^{max} = 5$ makes all models feasible. Interestingly, values of SL^{max} higher than 5 do not improve the outcome.

When fixing SL^{max} to one, the RS-SSP and RS-SSP-MU model are infeasible. The RS-SSP-MU-W model, in contrast, provides feasible solutions for servicing durations shorter or equal to one hour.

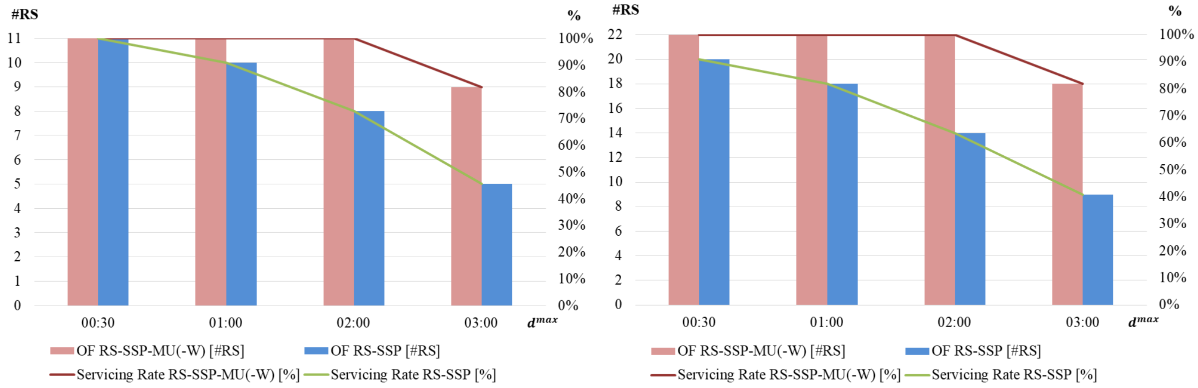
The last combinatorial parameter change considers varying values of d^{max} when assuming a headway of 15 minutes. Similarly to the single parameter change, varying servicing durations leads to mainly constant OF outcomes for the extended models even though the headway is decreased to 15 minutes. Moreover, the OF outcomes of the RS-SSP Base Model behave similar to the shorter headway when compared to the single parameter change (i.e. assuming a headway of 30 minutes).

Figure 5.14 visualises the decreasing values of the objective function for increasing values of d^{max}. While the blue bars present the course of the Base Model, the reddish bars show the course of the two extended models (i.e. RS-SSP-MU and RS-SSP-MU-W). In Figure 5.14a, it becomes clear that the extended models reach the maximum value of 11 RS units (i.e. servicing rate of 100%) already with a servicing duration of two hours, whereas the Base Model only achieves an optimal solution of 11 serviced RS units with a servicing duration of 30 minutes. Figure 5.14b visualises the impact of d^{max} when doubling the train arrival frequency. Note that the total number of RS units ($\#RS$) is 22 for the scenarios assuming a headway of 15 minutes (i.e. doubled train arrival frequency). The two extended model versions present objective values which are doubled as compared to the 30 minutes headway solution, while the servicing rates stay exactly the same. The performance of the RS-SSP Base Model, however, slightly downgraded by halving the headway.

Furthermore, Figure 5.15 shows the impact of SL^{max} assuming a servicing duration of three hours.

1^{st} Chang. Parameter	1^{st} Par. Value	2^{nd} Chang. Parameter	2^{nd} Par. Value	Objective Function		
				RS-SSP	RS-SSP-MU	RS-SSP-MU-W
d^{max}	03:00	SL^{max}	1	infeasible	infeasible	infeasible
			2	infeasible	infeasible	4
			3	infeasible	infeasible	6
			4	infeasible	infeasible	8
			5	5	9	9
			6	5	9	9
			7	5	9	9
d^{max}	00:30	SL^{max}	1	infeasible	infeasible	11
	01:00			infeasible	infeasible	8
	02:00			infeasible	infeasible	infeasible
	03:00			infeasible	infeasible	infeasible
d^{max}	00:30	headway	15 min	20	22	22
	01:00			18	22	22
	02:00			14	22	22
	03:00			9	18	18

Table 5.10: Impact of combinatorial parameter changes



(a) Impact of d^{max} with a 30 minutes headway

(b) Impact of d^{max} with a 15 minutes headway

Figure 5.14: Impact of d^{max}

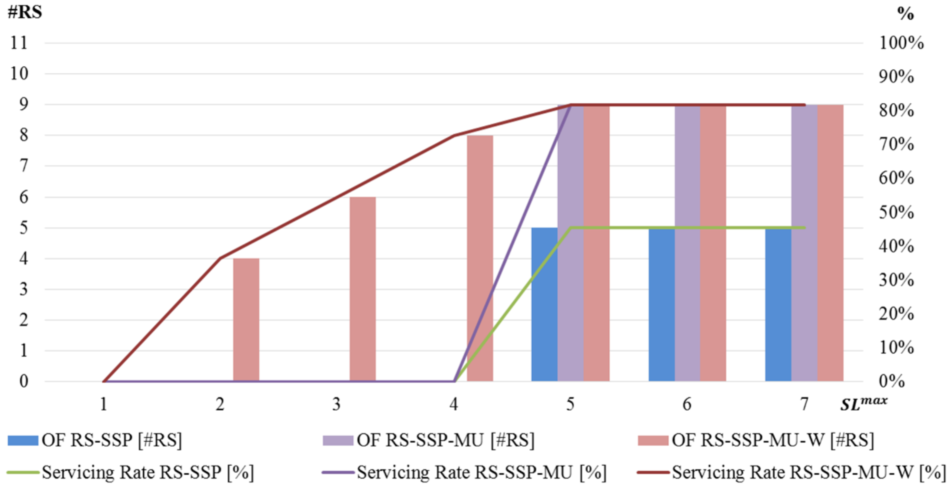


Figure 5.15: Impact of SL^{max} with d^{max} of 3 hours

To summarise, there are large differences between the RS-SSP Base Model and the two extended versions. Mainly, the short time horizon is a huge disadvantage of the Base Model. Both, the RS-SSP-MU and the RS-SSP-MU-W have a time horizon starting with the first arriving train and ending before the start of the peak hour. This time horizon comprises almost the entire time period in which daytime servicing could be done. Note that the time period after the evening peak is considered as night servicing. Certainly, the evening peak (i.e. 17:36 to 19:23) might also be considered for daytime servicing in case not all RS units are in operation. However, the BDU plan shows that the trains arriving in the evening peak hour are decoupled as they arrive in a train with a length of two RS units and depart in a train of one RS unit. In case an RS unit visited the SL at daytime already, it might happen that it rolls out towards the SL in the evening peak for the second time. The RS-SSP-MU-W model (as well as the two other models), however, cannot cope with RS units entering the SL twice per day. The model would thus need to be extended by the function allowing an RS unit to visit the SL multiple times while ensuring that RS units are not serviced multiple times per day.

Due to the short time horizon of the RS-SSP Base Model, the results significantly differ from those of the more extended models. The outcomes of the RS-SSP-MU and the RS-SSP-MU-W are very similar yet the RS-SSP-MU-W provides more feasible solutions with respect to low values for SL^{max}. This is due to the functionality of the RS-SSP-MU-W allowing RS units to wait for being serviced. The two extensions made on the RS-SSP Base Model were, thus, proven to be of high value.

Regarding the impact of the parameters, it can be concluded that both, the servicing (and shunting) duration d^{max} and the maximum allowed number of RS units being serviced simultaneously SL^{max} influence the result of the objective function. The extent of their impact depends on the tightness of their restriction. Obviously, changing both parameters in combination may tighten the limitations leading to even larger differences in the results as compared to the Base Scenario. The headway implied doubling the number of RS units and, therefore, strongly impact the model results. For the RS-SSP-MU and the RS-SSP-MU-W, however, the results were just doubled and the servicing rate did not change. For the Base Model, in contrast, the halving of the headway implied a further shortening of the time horizon. As a consequence, even lower servicing rates were achieved by the Base Model. Note that with a headway of 30 minutes, the value of the objective function achieved by the Base Model equals the number of available RS units (i.e. 11 RS units) for a 30-minutes servicing duration (i.e. $d^{max} = 00{:}30$), whereas with a headway of 15 minutes, the objective function has a value of 20 RS units completing servicing out of 22 available RS units. The shorter headway, thus, leads to a worse servicing rate for the RS-SSP Base Model.

With respect to the final subquestion about supportive adaptations from the side of NS, it can be concluded that changing several input parameters have positive influence on the maximum number of RS units being serviced during daytime. Obviously, lower train frequencies, higher service capacities, shorter servicing durations, larger turning times, faster RS exchanges, and additional RS units standing at the SL never downgrade the outcome, yet they do not automatically enhance results. As shown for the case of the Sprinter train series 5600 between Zwolle and Utrecht, there are critical values which need to be respected (e.g. with respect to tt_k, tt^{min}, SL_0, and SL^{max}). When extending the RS-SSP on other train series, these critical values would need to be specified. Accordingly, supportive adaptations on the timetable or servicing efficiency can be discovered.

6

Applicability of the RS-SSP

In the previous chapter the fifth subquestion was answered based on time input parameters. In this chapter the answer to the subquestion – *“What adaptations at NS may support the applicability of the RS-SSP?”* – can be completed with respect to the system of NS in general. Also, the sixth and last subquestion – *“How does the RS-SSP impact different stakeholders?”* – is addressed. The following paragraphs are divided per subject. First, the potential of the current RS-SSP model version is presented, followed by the applicability of the RS Exchange Concept. For each subject, the functionality of the RS-SSP is discussed. While strengths of the RS-SSP are stated, challenges are remarked and supportive actions for implementing the RS-SSP are provided. Note that most aspects concerning the strengths and challenges of the RS-SSP arose from the interview analysis of Chapter 3.

Service locations The most advanced model of the RS-SSP (i.e. RS-SSP-MU-W), developed in this master thesis, could be solved independently for individual service locations. This leads to far better solutions as opposed to the current situation. While in the current situation no RS units are serviced during daytime, the RS-SSP yielded solutions allowing all RS units of a train series to be serviced during daytime. This is clearly a great success and can be seen as a strength of the RS-SSP. However, solving the model individually per service location does not lead to optimal results for an entire network. For applying the model to a larger network, the model should be extended by considering multiple service locations.

RS types As long as a train series operates with a single RS type or operates trains running with a single RS unit, the RS-SSP is absolutely applicable and yielding feasible solutions. However, as the RS-SSP does not differentiate between RS types, it may provide infeasible solutions for train series with multiple RS types. Such an infeasible solution indicates, for instance, that two RS units of different types are coupled together. As most train series operate with multiple RS types (e.g. the Sprinter train series 5600), it is advisable to take multiple RS types into account.

Time horizon While rolling stock circulations are typically planned on a week horizon, the RS-SSP-MU-W only considers a time horizon of approximately ten hours ending with the last train departure before the evening peak. The RS-SSP-MU-W is limited to this time period because it does not allow RS units to enter the SL multiple times, yet in the evening RS units start to roll out towards the SL. Even though RS units rolling out in the evening are not considered for daytime servicing, it may be favourable to enlarge the considered time horizon of the RS-SSP. The RS units entering the SL before the evening peak would, for instance, have more time to complete servicing when extending the time horizon. This may also improve the model results. As the BDU plan consists of one standardised week, a time horizon of one week might be suggested for the RS-SSP. The advantage of a time horizon of multiple days is the possibility of tracing RS units over several sequential days. This would also allow to check whether a certain RS unit can be serviced during daytime at several sequential days in order to meet its 24-hour cleaning deadline.

Generally, it can be concluded that the RS-SSP may require a few further extensions in order to be used adequately on larger scale. The RS-SSP presents advantages with respect to model extensions based on the type of the model. Remember that a MILP model was chosen for allowing further extensions on the model.

Clean trains in the morning By means of the RS-SSP more RS units can be serviced than with the current cleaning procedure. Especially regarding the expected increasing servicing demand, this is a great advantage of the RS-SSP over the current cleaning procedure. However, passengers are more sensitive to dirt and bad smell in the morning than in the afternoon or evening. Servicing and cleaning RS units during daytime may imply that RS units become dirty during operations in the afternoon and evening. As night servicing is skipped for RS units having completed servicing during daytime, they might be dirty when starting to operate the following morning. In order to guarantee satisfaction by passengers, Anonymous (2019) suggests cleaning each train before or after its trip when implementing the RS Exchange Concept. It should be notified that this would only imply a basic cleaning entailing emptying bins and removing major dirt. Actually, it might be seen as an enhancement of the current executed *keerpuntreiniging*, which comprises emptying garbage bins in trains standing at turning stations.

Additional expenses In the framework of this thesis costs are not explicitly taken into consideration. However, according to Anonymous (2019) several technicians are underemployed at the SL during daytime and thus searching for work. Due to the low availability of RS units during daytime, there is currently only little work to do for technicians. Nonetheless, they need to be employed during daytime according to the national regulations. Increasing the number of RS units to be serviced by means of the RS Exchange Concept can also improve the work efficiency of technicians. Furthermore, night work hourly rates are higher than daytime work. Replacing night workers by daytime workers would thus even reduce costs. However, it is rather unlikely that night workers can actually be reduced because of the expected increasing number of RS units. Daytime servicing should thus be seen as a solution for increasing the capacity at service locations rather than decreasing costs. Therefore, additional expenses involved with the implementation of the RS-SSP should be contrasted against other capacity increasing solutions – not against the current situation.

With respect to additionally required personnel, train drivers should be addressed. The train driver arriving at the turning station where an RS exchange occurs could be reallocated to the substituting RS unit running in the following departing train. An additional train driver would be required to drive the serviced substituting RS unit from the SL to the station. The same train driver could, then, drive the 'dirty' RS unit to the SL. However, according to Van Wersch (2019) and Anonymous (2019), it might take a while until the train driver bringing the RS unit towards the SL becomes available again. The reason for this is partly based on large walking distances at service locations. Due to the long unavailability of a train driver arriving at the SL, multiple additional train drivers may be needed for one single SL. As the purpose of the RS-SSP is to be extended to an entire network (e.g. the Dutch railway network), various service locations would be used for daytime servicing. Certainly, the number of additional required train drivers increases with additional involved SLs. Note that, with respect to the future, train operations may automatise, lowering the demand for train drivers. In the short-term, however, train drivers do play an important role.

Furthermore, the suggested basic cleaning before or after each train trip may request a substantial number of additional cleaning personnel.

Accessibility of service locations The selection of Zwolle as a suitable SL for computational experiments was, inter alia, based on the good accessibility of the SL as opposed to Utrecht. Aside of accessible pathways, the working procedures may vary between service locations (Anonymous, 2019) as well as walking distances at the SL and service capacities. Remember that SLs also feature different equipment. An exterior washing machine is, for instance, only available at certain SLs (Janssens, 2017). Extending the RS-SSP, thus, also implies a wise selection of service locations. Good accessible shunting paths towards and from the SL, short walking distances at the SLs, and a broad spectrum of equipment can be seen as advantageous.

Operational disruptions The daytime servicing time intervals may be seen as servicing buffer times. In case an RS unit cannot comply to its planned servicing time interval during daytime, due to an operational disruptions, it is assumed that it can be serviced during the night shift. This means that there are more possibilities for an RS unit to meet its servicing deadline. As a consequence, the servicing performance rate will be improved. Furthermore, with respect to a constant annual servicing demand, the servicing demand at night can definitely be reduced by means of the RS-SSP leading to lower work pressure and greater employee satisfaction. Despite the advantages of additional servicing buffer time during daytime, it may worsen the predictability of workload during the night shift.

Misalignment between RS controllers and SL managers A strong cooperation between RS controllers and SLs represents a prerequisite for enabling RS exchanges. While the first priority of the RS controllers concerns the compliance to the timetable, the performance of the service locations is measured by the percentage of RS units being serviced in time and with the appropriate servicing quality. The varying prioritisation provokes complications in the cooperation of the RS controllers with the SLs. Even though both parties are aware of this problem and NS have already tried to solve the disparities by incorporating the subsidiary company NedTrain into the parent company NS, the problem is still present. Therefore, the KPI targets of the RS controllers and the managers of the service locations should be aligned.

Traffic increase The traffic during daytime at and around stations may increase because of the additional RS movements implied by the RS exchanges. A higher traffic amount leads to a higher track usage, which needs to be requested by ProRail at an early stage. In addition, ProRail is responsible for the coordination of the rail traffic including the scheduling of shunting movements, which is also impacted by increasing traffic. Both, the changes in track usage and in coordination may affect competing railway companies. This effect on other railway companies would be regulated and communicated by ProRail. Perhaps, increasing traffic may also imply less or shorter time windows with respect to track maintenance. However, the tracks at and around the station may probably not be available for maintenance during daytime even without additional RS movements. Generally, good and timely communication with ProRail is crucial for enabling the implementation of the RS-SSP.

Cooperation between rail operator and infrastructure manager With respect to good communication between ProRail and NS, the relationship between the two companies should be reflected. As described in Section 3.1, the separation of NS and ProRail can cause incentive misalignments due to different goals. According to Van de Velde (2018), investments and higher train densities may even enhance the importance of misalignment issues. As mentioned before, the implementation of the RS-SSP implies investments from side of NS (e.g. additional train drivers and cleaning personnel) as well as higher train densities at and around a station. The latter may also evoke investments from side of ProRail regarding an extension of the railway infrastructure around stations. Therefore, the separation may be seen as challenging for the implementation of the RS-SSP. The realignment arrangement *Better for More* is already tackling the inconsistencies in prioritisation between the two parties. However, it might be supportive to analyse potential advantages of the RS-SSP for ProRail in order to improve the cooperation with ProRail. It should be remarked that NS (and ProRail) are taken as example, however, the discussion may also refer to other national railway companies featuring vertical separation (e.g. the National Railway Company of Belgium).

Applicability to other public transport systems Due to its network perspective, the RS-SSP is a very generic model, which cannot only be applied to multiple railway companies but also to other public transport systems such as metro, tram, and bus networks. As metro and tram networks also involve track infrastructure, they face large similarities to railway networks facilitating the applicability of the RS-SSP. Due to less differences in RS types, the current RS-SSP version might even be more suitable to metro or tram operations than to railways. Aside of overland transportation, the RS-SSP may also be interesting for the fleet management in air or water traffic. However, airlines may have additional requirements with respect to competing airlines being serviced at the same node (i.e. airport). Regarding water traffic, ferries with regular line service might be considered. To what extent the RS-SSP is applicable to airlines or ferries would need to be further investigated. To sum up, the strengths, challenges, and supportive actions as described above do not only apply to NS yet address all companies implementing the RS-SSP.

The main aspects addressed in this chapter can be summarised as follows:

Strengths of the RS-SSP

1. Increased number of RS units being serviced during daytime
2. Feasible solutions for train series operating with a single RS type
3. Allowing to easily extend the model
4. Complying with cleaning deadlines
5. Increasing total capacity of SLs
6. Decreasing servicing demand at night
7. Higher work efficiency of technicians during daytime
8. More buffer time for servicing tasks
9. Improved coordination between RS controllers and SLs
10. Generic model applicable to multiple public transport operators

Challenges for implementing the RS-SSP

1. Yielding optimal and feasible solutions for an entire network
2. Tracing RS units over several sequential days
3. Great need for cleanliness in the morning
4. Necessity of additional train drivers and cleaning personnel
5. Poor accessibility of certain SLs during daytime
6. Predicting the workload at SLs
7. Required cooperation between RS controllers and SL managers
8. Impact of higher traffic at and around turning stations

Supportive actions

1. Consideration of multiple service locations
2. Differentiation between RS types
3. Extended time horizon towards one week
4. Basic cleaning of each train before or after its trip
5. Additional train drivers or automated trains
6. Sufficient servicing personnel during daytime
7. Wise selection of service locations to be available for daytime servicing
8. Aligning KPIs of RS controllers and SL managers
9. Good and timely communication with ProRail
10. Analysis of potential advantages of RS-SSP for ProRail

7

Conclusions and Recommendations

The goal of this research was to answer the following research question – *How to use the capacity at service locations more effectively?* To answer the main research question, six subquestions have been formulated, which are explicitly answered in Section 7.1. Remember that the answers to the subquestions resulted from the current state analysis, the development of the Rolling Stock Servicing Scheduling Problem (RS-SSP) model, and the computational experiments. While Section 7.1 provides the conclusions of the research, Section 7.2 offers recommendations with respect to model extensions and further research as well as to practices at NS and Arcadis.

7.1. Conclusions

The current state analysis has shown that the service locations are very busy during the evening and night as most RS units are operating during daytime. Furthermore, the servicing demand during the night already exceeds the servicing capacity at several NS service locations. In 2030, however, the expected total servicing demand will exceed the total servicing capacity by far. Therefore, there is great need for a more effective usage of the service locations.

Analysing the RS movements yields that several RS units roll out towards an SL after the morning peak, waiting for being required for the peak operations in the evening. Mainly because of the low number of RS units standing at an SL during daytime, it is not worth hiring cleaning personnel for cleaning the RS units from the inside. Due to national regulations, technicians are available at SLs during daytime. Their work efficiency, however, is very low based on the small number of RS units. With respect to the first subquestion – *Which requirements and restrictions play an important role for daytime servicing?* – complying with the timetable may be seen as one of the most important restrictions. In addition, increasing the availability of RS units at SLs during daytime represents a great need regarding the efficiency of daytime servicing.

In order to more effectively use the capacity at SLs, the RS-SSP has been developed, introducing the RS Exchange Concept. The idea of this concept is to fully service (i.e. exterior and interior cleaning, technical checks, and repair if required) the RS units rolling out towards the SLs after the morning peak. As soon as the RS units have completed servicing, they are provided for an exchange with operating RS units arriving at their turning station nearby the SL. By means of the RS exchange, the number of RS units visiting the SL can be increased and thus the number of RS units being serviced during daytime can be raised. The RS units having completed daytime servicing do not need to be serviced during the night. With respect to the current servicing demand, servicing tasks are shifted from the night towards daytime, reducing the servicing demand at night. This may solve the existing capacity lack of SLs. Regarding the expected increase in servicing demand by 2030, the total servicing demand at night might not (substantially) decrease in comparison to the actual servicing demand. The additional servicing demand, which exceeds the total servicing capacity of all SLs at night, however, could be performed during daytime. Here, the servicing capacity is literally increased. The second subquestion – *Could a rolling stock exchange support daytime servicing?* – can thus be answered positively.

The RS-SSP model represents a decision support model, indicating when an RS exchange should occur in order to maximise the total number of RS units completing servicing during daytime. Due to the model constraints, multiple needs and requirements from the side of the rolling stock planning and from the service locations are taken into account. A solution yielded by the model needs to comply, for instance, with the timetable according to the BDU plan. These components are answering the third subquestion – *What information, knowledge and data is required for a decision support model?* Subsequently, the fourth subquestion – *Which functions should a decision support model feature in order to improve the capacity usage at service locations?* – is addressed. The functionality of the RS-SSP should entail the maximisation of the number of RS units being serviced during daytime. Therefore, the model needs to enable full daytime servicing and allow RS exchanges. The requirements for building the model are the model components (e.g. parameters and variables), which are used for formulating the objective function and constraints.

Within the framework of this master thesis three model versions have been developed. While the first model represents the Base Model of the RS-SSP, the second model (i.e. RS-SSP-MU) is an extended version of the Base Model allowing trains to run with multiple RS units. The third model (i.e. RS-SSP-MU-W) is a further extension of the RS-SSP-MU also allowing RS units to wait at the SL for being serviced.

The RS-SSP model has been applied to the Sprinter train series commuting between Zwolle and Utrecht considering Zwolle as only available SL for daytime servicing. According to the model results, all eleven RS units being used for this train series could complete servicing during daytime. As currently no RS units are fully serviced during daytime, this outcome promises great success of the RS-SSP with respect to a more effective capacity usage at SLs.

As multiple input parameters are based on assumptions, the model was tested on parameter changes. Due to possible timetable changes in the future, the timetable provided by the BDU plan was also adjusted for experimenting. The outcome of the analysis revealed that the model is more sensitive to certain parameters than to others. The minimum required turning time of an RS, for instance, is only binding when it equals the actual turning time of a train. In case it exceeds this critical value, the model is infeasible. The duration of servicing and shunting, in contrast, can influence the size of the outcome. With respect to the previous example, a servicing and shunting duration of two hours led to 11 RS units being able to complete servicing during daytime, whereas a duration of three hours decreases the outcome to 9 RS units. Not only extending the servicing and shunting duration may worsen the model results, but also decreasing the maximum allowed number of RS units being serviced simultaneously. Furthermore, tightening the two parameters in combination downgrade the outcome even stronger. Obviously, critical values can be specified for all parameters with respect to achieving the optimal number of 11 RS units able to complete servicing during daytime. In case all parameters are set to their critical values, all parameters are binding, meaning that there is no buffer (e.g. no buffer time).

With respect to the applicability of the RS-SSP, multiple strengths could be identified. The capacity at SLs, for instance, can be increased by means of implementing the RS-SSP. Furthermore, the work pressure of night workers might be decreased by balancing the workload over the entire day. This may lead to a higher employee satisfaction. In addition, the servicing performance rate can be improved as the possibility of daytime servicing provides additional buffer time.

Despite of the advantages, several challenges need to be overcome when implementing the RS-SSP. In order to yield optimal and feasible solutions on a large scale and trace RS units over several sequential days, the current RS-SSP model version requires further extensions. Furthermore, the strong need of passengers for clean trains in the morning needs to be addressed when switching from servicing at night towards daytime. Moreover, the RS Exchange Concept implies additional train drivers as long as automated trains are not used. Also, sufficient servicing personnel needs to be available during daytime, which might require additional employments. Furthermore, the poor accessibility of certain SLs may cause difficulties for daytime servicing. In addition, operational disruptions can cause deviations from the plan. This may lead to reallocations or even cancellations of servicing appointments during daytime. In addition, the differences in prioritisation of RS controllers and SL managers complicate the cooperation between the two parties, which is considered as a prerequisite for implementing the RS-SSP.

Both the experiments as well as the challenges pose incentives for the fifth subquestion – *What adaptations at NS may support the applicability of the RS-SSP?* Firstly, NS should specify the critical values for all parameters and ensure that these values can be applied with appropriate buffer. Furthermore, the supportive actions as listed in Chapter 6 may help face the above mentioned challenges.

Also, the sixth and last subquestion – *How does the RS-SSP impact different stakeholders?* – refers to the strengths and challenges of the RS-SSP. While most strengths positively affect the railway operator NS, the balanced work load has positive influence on the employee satisfaction. Passengers may be pleased by improved servicing rates yet unsatisfied in case of dirty trains in the morning. Furthermore, the infrastructure manager (ProRail) and competing railway companies might be affected by the increased traffic densities at and around stations.

In conclusion, to answer the main research question, the RS-SSP proved to increase the capacity usage at service locations by allowing daytime servicing.

7.2. Recommendations

In this section recommendations are presented with respect to the implementation of the RS-SSP model and the RS Exchange Concept relating thereto. It should be mentioned that the RS Exchange Concept has only been analysed with respect to the RS-SSP model. Therefore, statements regarding the RS Exchange Concept are subject to the usage of the model. Firstly, recommendations are provided regarding further model extensions. Secondly, recommendations address the need for further research topics and, finally, practical advice is provided for NS and Arcadis.

Recommendations for Further Model Extensions

As mentioned above the RS-SSP-MU-W represents the most advanced RS-SSP model so far. This model is based on a current state analysis. However, multiple assumptions are taken into account with respect to input parameters. Moreover, the current model version assumes a single SL to be available for daytime servicing. The model does not differentiate between RS types and cannot handle RS units to enter the SL twice. Hence, its usage is still limited. Several model extensions, however, may already increase the applicability of the model significantly. The feasibility of the RS-SSP implementation also requests further research as described in the following paragraph.

Starting with advisable model extensions, differentiating between RS types seems to be the most urgent yet easiest extension to the RS-SSP-MU-W. The urgency of this model extension is based on the usability of the model. It should be remarked that differentiating between RS types may also allow the consideration of multiple train series. By now, all trains considered by the model run in the same train series, allowing to randomly allocate RS units towards departing trains. In case multiple train series are taken into account, the RS allocation is restricted with respect to differences in RS types. Note that a single RS unit may operate in multiple train series operating with equal RS types.

Furthermore, the model should be extended with respect to multiple service locations. Obviously, the RS-SSP-MU-W can already individually be applied to multiple SLs, however, the connection between SLs is not integrated in the model yet. This would be required in order to achieve optimal results on a larger scale.

The last advisable extension to the RS-SSP-MU-W is based on the time horizon. While the current time horizon considers approximately 10 hours, extending the time horizon towards an entire day may be useful and allows improved outcomes. However, a time horizon of a week would also provide information about whether a specific RS unit can be daytime serviced on several consecutive days or not. Remember that RS units have an interior cleaning deadline of 24 hours, so it is preferable that they are cleaned more or less at the same moment every day.

The three most important model extensions are listed below. The enumeration follows the urgency of the extension with respect to the usability of the model as described above.

Advisable extensions to the RS-SSP-MU-W

1. Considering multiple RS types
2. Considering multiple SLs
3. Considering a time horizon of an entire day (i.e. 24 hours) up to a week

Recommendations for Further Research

The following paragraph proposes further research topics relevant for implementing the RS-SSP. Firstly, the diverse service locations need to be analysed in order to wisely select suitable SLs being available for daytime servicing. Keep in mind that SLs feature multiple differences such as accessibility, capacity, equipment, shunting durations and walking distances. The characteristics of an SL may be crucial for the success of the RS Exchange Concept. An analysis on the accessibility and functionality of SLs will thus be required when testing the RS-SSP on multiple service locations.

A further research topic should address the passenger and employee satisfaction. Here, it might be advisable to undertake a survey and to discover the most important aspects with respect to satisfaction. Note that both the passengers' and the employees' points of view are very important when thinking about a system change such as caused by the RS-SSP. This is based on the fact that the profitability of NS is highly dependent on the revenue paid by its passengers and the service achieved by its employees.

Furthermore, a cost-benefit analysis should be undertaken in order to evaluate the advantages and disadvantages of the RS-SSP. Obviously, the outcome of the passenger and employee satisfaction study may also be used for the cost-benefit analysis. Therefore, it is advisable to follow this order when executing further research. By means of a cost analysis an estimation of the additional expenses can be achieved as implied by the RS-SSP implementation.

The last research topic consists of a comparison between the RS-SSP and other methods solving the lack in capacity at SLs. As this master thesis mainly focused on the RS-SSP, other solutions might have been addressed in Chapter 3 yet not been analysed into detail. In order to ensure that the RS-SSP represents a good solution, it should be compared to other solutions. The cost-benefit analysis, as suggested before, might provide contrastable aspects to be used for the comparison.

The overview below summarises the recommendations regarding further research topics including the suggested execution sequence.

Further research topics

1. Analysing service locations
2. Analysing passenger satisfaction
3. Analysing employee satisfaction
4. Cost-benefit analysis for implementing the RS-SSP
5. Comparing the RS-SSP with other methods solving the lack in capacity at SLs

Recommendations for NS

Obviously, the execution of the suggested model extensions and further research are part of the practical advice for NS. With respect to timetable changes or improved servicing durations, critical values should be specified. Remember that all input parameters of the model feature a critical value. Exceeding the critical value may imply either an infeasible solution or a worse solution, depending on the parameter. Relaxed values, on the contrary, do not further improve the model results as they become unbinding. Knowing the critical values for each of the input parameter thus provides information about the slightest adjustments to be made by NS in order to achieve the best possible outcome. It should be mentioned that it is not preferable to tighten all parameters towards the critical value. Yet the effort is probably lower when minimising the adjustments to be made by NS. Moreover, some buffer between the parameter value and its critical value may be important for robustness.

Furthermore, it is advisable to align the KPIs of RS controllers and SL managers in order to avoid the disparity in prioritisation. This may help to achieve a better cooperation between the two parties. This will hardly be necessary when implementing the RS-SSP in reality.

The interview analysis provided information about a change in the cleaning system at service locations. Instead of having fixed days at which certain interior cleaning tasks are always executed, cleaning tasks shall be executed with respect to urgency. This new cleaning system shall be implemented by January 2020. It might be too late to take the impact of the RS-SSP and the suggestions provided in this master thesis into consideration before implementing this new cleaning system. However, before implementing any further system changes the preferences and influences of the RS-SSP should be respected.

In order to avoid dissatisfied passengers due to dirty trains in the morning, the already existing *Keerpuntreiniging* should be enhanced by a basic cleaning of each train before or after its trip. Obviously, this implies additional cleaning personnel, however, it may also reduce the daily cleaning duration at the service locations.

While the additional cleaning personnel would need to be requested by the outsourced cleaning company Hago, train drivers need to be provided by NS. Note that as soon as automated trains are used, the need for train drivers will decrease.

The last important aspect to be considered by NS is a good and timely communication with ProRail. As the RS Exchange Concept has high impact on the traffic volume at and around SLs, the track occupation needs to be negotiated with ProRail.

Practical recommendations for NS

1 Execution of model extensions and further research as suggested above
2. Specification of critical values of input parameters
3. Considering critical values for timetable adjustments and servicing improvements
4. KPI alignment of RS controllers and SL managers
5. Take RS-SSP into consideration when changing cleaning system
6. Implementation of basic interior cleanings before or after each train trip
7. Provision of additional train drivers and servicing personnel
8. Good and timely communication with ProRail

Recommendations for Arcadis

The RS-SSP also presents potential task fields for Arcadis as a design, consultancy, engineering, project and management company. Certainly, Arcadis can support and advice NS with respect to analysing the further research topics and implementing the RS-SSP. However, the gained expertise is not only relevant for NS, but also for other public transport operators struggling with servicing capacities. Arcadis may, thus, proactively contact public transport operators (e.g. metro, tram, and bus companies) and propose the concept of the RS-SSP. Also, the applicability of the RS-SSP for the fleet management in air traffic presents a potential research project for Arcadis. In case of interest, multiple implementation projects could arise. As opposed to competing consulting companies, Arcadis features the professional expertise with respect to the functioning and applicability of the RS-SSP. Moreover, it has specialised departments for public transport projects (e.g. the departments *Integrale Plannen* and *Railstudies en Projectmanagement*).

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A

Interview reports

Interview reports have been made of the conducted interviews. In the following, those reports can be found listed according to the date of executing the interview.

A.1. Michiel ten Broek (Arcadis), 5 May 2019

Ten Broek is a senior specialist of rail traffic knowledge at Arcadis. Before working at Arcadis, he was an employee at NS Reizigers. Therefore, he has multiple contacts with NS and insight into the rolling stock maintenance planning processes.

Ten Broek explained that the largest problem with respect to the night shift at service locations is the lack in physical (i.e. stabling) capacity, especially in the Randstad. Furthermore, the interior cleaning capacity represents a bottleneck (e.g. in Roosendaal). Speaking about possible solutions for those capacity issues, Ten Broek indicates to increase the capacity usage of the service locations by using the capacity multiple times within one night. This might be done by stabling the serviced rolling stock outside the service location in order to make space for other rolling stock, which requires interior cleaning. Such a solution has already been implied at the service location in Alkmaar. In Alkmaar the first trains already roll in the service location at 7pm. Therefore, they already start to clean the interior of the rolling stock at 7pm. As soon as a train is serviced, it is driven to Zaandam, Beverwijk, Uitgeest or other locations where tracks are reserved. New incoming trains have then sufficient space at the service locations and can be serviced. In total, there are 3 cleaning shifts per night. By means of this shift system, the physical capacity is used more efficiently. However, to assure fast cleaning, more cleaning personnel is required.

Another solution might be to extend the service hours by the evening. Ten Broek thinks that the new high frequency program “Programma Hoogfrequent Spoorvervoer” (PHS) would even support such an extension. As much less trains will run after the evening peak as compared to during the peak hour and to the day-hours between peak hours, a large number of trains may directly go towards the service locations. Hence, those trains can be serviced earlier and it is in fact the same reason why the Alkmaar-method could be implemented.

Ten Broek does not think that servicing trains between the morning and evening peak represents a solution as the system (that is to say: NS-management) asks for clean trains in the morning. Hence, cleaning trains during daytime would not prevent those trains to be cleaned at night, which would lead to double work. First, the system would need to change before cleaning during daytime may solve the capacity issue. Besides, according to Ten Broek, there are not sufficient trains available for daytime servicing as only few trains are out of operation between morning and evening peaks.

A.2. Bob Huisman & Jordi Zomer (NS), 21 May 2019

Bob Huisman is Manager Maintenance Research and Development at NS and Jordi Zomer is a working student at NS and involved in the programme Service & Stabling. The programme Service & Stabling is responsible for realising sufficient capacity at service locations.

Problem description

According to Huisman and Zomer, there are two important problems with respect to allowing trains to be serviced during daytime. On the one side, there is a lack in rolling stock being available for servicing during daytime. Hence, more rolling stock units should be available for servicing during daytime. On the other side, the interior of rolling stock needs to be cleaned every 24 hours. This means that if a rolling stock unit gets cleaned during daytime on one day, it should also get cleaned on the following day during daytime. However, this represents a complex puzzle as a certain rolling stock unit does not have the same route every day, but circulates through the entire Dutch railway network.

Certainly, it is possible to plan that each rolling stock unit has the same route every day (or every week day) ensuring that a certain rolling stock unit passes the same stations at the same moment in time every day. However, such a strict planning would not be flexible to disturbances and imposes multiple restrictions, which does not make it desirable.

The question arises whether a rolling stock unit passes often enough and regular enough at a node (i.e. station), where it can be serviced. At this moment, NS is not able to answer this question because the system is not predictable enough. Even though the rolling stock allocation is planned in advance, the number of operational adjustments is very large leading to unpredictable rolling stock circulations.

NS is trying to find a solution for both of the above described problems. Thus, the solution should increase the number of rolling stock units available for servicing during daytime and generate interior cleaning every 24 hours. This might be done by bringing more rolling stock units to the service locations during daytime.

Rolling Stock Exchange Concept

The idea is to exchange operating (dirty) rolling stock units with cleaned rolling stock units being in reserve at service locations during daytime. Zomer explains that multiple train series show lower frequencies between the morning and evening peak. Besides, the number of rolling stock units per train is higher in the peak hours as compared to the off-peak hours. Therefore, the residual rolling stock units are driven towards service locations, get cleaned and then wait (2 to 8 hours) until they are used for operation in the evening peak. Those residual rolling stock units are thus on reserve at service locations. Exchanging operating (dirty) rolling stock units with those cleaned rolling stock units on reserve may increase the number of rolling stock units visiting the service locations during daytime. Hence, there would be more rolling stock units available for daytime cleaning and also the chance that a certain rolling stock unit visits a service location during daytime increases. The latter also increases the chance that rolling stock units, which get cleaned during daytime, get cleaned every 24 hours.

Zomer is currently working on measuring the effects of such rolling stock unit exchanges. Therefore, he is establishing a simulation model. Here, historic data about rolling stock allocations is used as input for the model. Then, data are adjusted allowing rolling stock units to get exchanged virtually. The simulation model is finally showing the effects in case rolling stock unit would have been exchanged. The idea is to maximise the number of rolling stock units serviced during daytime. It is assumed that rolling stock units, which have been cleaned during daytime, do not get cleaned at night anymore. Zomer hopes that these rolling stock units can be serviced on the following day during daytime again. Otherwise, the model assumes that these rolling stock units will be cleaned in the following night – implying a meantime between interior cleaning of 36 hours instead of the desired 24hours.

Zomer and his team are analysing which rolling stock units can be used for a rolling stock exchange in general. However, for now (in the simulation model), they make assumptions about which of the potential rolling stock units (virtually) get exchanged. Certainly, there is more research required in order to select the rolling stock units in an optimal way, for instance, by maximising the number of rolling stock units getting serviced during daytime.

As mentioned before, the frequency of the interior cleaning of rolling stock is about 24 hours. Technical checks, on the contrary, have a frequency of 48 hours and exterior cleaning is in general executed once in a week or even only once in multiple weeks. Ensuring regular daytime servicing is thus essential for interior cleaning, whereas it plays a minor role for technical checks, let alone for exterior cleaning. As the predictability of small reparations is very low, it is not even taken into consideration for this analysis. Furthermore, the interior cleaning is performed by an external company, called Hago. Hago is dependent on the number of rolling stock units provided by NS during daytime. Hence, NS sees high relevance in increasing the number of rolling stock units being available for interior cleaning during daytime in order to improve the capacity usage at service locations.

In addition, Zomer and his team are analysing whether rolling stock exchanges would have been possible at service locations in practice. There is no generic method yet to check the feasibility from the side of the service locations, so for now they started with a testing sample in Zwolle asking the planners for a feasibility check.

According to Zomer, Zwolle represents a good starting location for three reasons:

1. In Zwolle is a large number of rolling stock units standing on reserve during daytime. Hence, there are already rolling stock units available for daytime cleaning.
2. As a consequence of the first reason, there is already cleaning personnel available during daytime.
3. There are 4 turning train series at Zwolle, so there is potential for exchanging rolling stock units.

When considering daytime cleaning as a solution to increase capacity at service locations, it is important to ensure that rolling stock units do not get cleaned twice: during daytime and at night. Huisman and Zomer explained that a database records when which rolling stock unit has been cleaned and which rolling stock unit requires which services. However, at multiple locations, there is a strict plan indicating which services have to be executed. Even though services are not necessary, they are executed according to the planning. This means that double work cannot be prevented with such a strict servicing plan. A dynamic planning, on the contrary, would support the prevention of double work because it is flexible and not restricted to a strict plan.

To conclude, there are two main aspects regarding the rolling stock exchange concept which require further research. On the one hand, the national distribution of the rolling stock circulation and, on the other hand, the detailed development of the nodes (i.e. stations).

A.3. Wouter Fleuren (NS), 5 July 2019

Fleuren works as an industrial engineer in the maintenance development at NS. He is mainly engaged in the logistical planning of the nodes (i.e. stations and adjacent service locations).

Planning system

Fleuren explains that the planning system consists of four major components, namely the timetable planning, the rolling stock planning, the node planning and the personnel planning of the network. Even though the personnel planning, i.e. train driver and train manager, plays an important planning component, it is less relevant for this subject and thus not further analysed. First, the timetable is planned indicating the departure and arrival time of trains at train stations. Hereby, all stations need to be connected and for the frequency determination the passenger demand is taken into account. Actually, everything important to the passenger is given in the timetable. The timetable is used as basis for the rolling stock plan. The objective of the rolling stock plan is to use the available rolling stock as efficient as possible in order to meet the passenger demand. Hence, the train lengths including the rolling stock type and the number of rail wagons are determined according to the required train capacity. As one rolling stock unit may consist of multiple wagons, the length of a train can be indicated more precisely by the number of wagons than by the number of rolling stock units. The rolling stock plan also adapts the platform at which a train shall arrive and depart specified in the timetable in case the previous selected platform does not provide sufficient capacity for the length of the train. Furthermore, the rolling stock plan represents the complete rolling stock circulation including the service and maintenance routing. According to Fleuren, the rolling stock planning can be divided into two parts, namely the rolling stock allocation based on the timetable and on the network balance. The first allocates the rolling stock such that the timetable can be applied, whereas the latter regulates the balance between the number of trains arriving and departing at service locations. Besides, the circulation of the train drivers and the crew needs to be planned, which may lead to additional train movements outside of the timetable. While the timetable and the rolling stock plan concern the entire (Dutch) rail network, the node planning analyses the rolling stock movements within a node. Note that a node [12] may consist not only of a station, but also of one or multiple adjacent service locations. A node plan is, thus, a plan for the entire

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[12] The definition of a node used by NS is: *"A node is a location in the rail network where rolling stock is stabled, maintained, cleaned and prepared for the passenger service. Hence, a node is a supplier for the rail network and, thus, for the transport process."* (Fleuren, 2019)

(i.e. integral) node from the moment that the passengers alight at a station until the train is ready for boarding. Hence, a node plan entails when and via which paths rolling stock units drive towards a service location, how they shunt within a service location, where they are stabled, when, where and by whom they are serviced and in which train each rolling stock unit departs. On behalf of the node plan, the rolling stock plan is checked for feasibility for the nodes, and if necessary adjusted. Obviously, the feasibility of the rolling stock plan regarding its own scope (i.e. the network and some local norms for the node planning) is checked while making the initial rolling stock plan; however, the interactions between rolling stock plan and node plan are so complicated that an integral feasibility check for the node is required when the rolling stock plan is completed. This node plan can be generated by a generic tool called *"Hybrid Integral Planning method"* (HIP). HIP is a module of the *"Behandelcalculator"* (BC), which consists also of a database, an instance generator and an analysing tool determining whether a plan works or not. The BC [13] may support all planning phases of the node planning as will be mentioned in the next paragraph. All NS service locations are incorporated in HIP.

Despite of the different planning aspects, the three planning components do all feature the same level of detail. The precision of the three plans is up to ten seconds – even though the timetable given to the passengers is in full minutes.

Planning phases

Within the planning system, there are three planning phases featuring distinct objectives: The strategical, tactical and operational planning. The strategical planning phase takes place about 2 to 10 years in advance and tries to determine the existing and required capacity. For the node planning, for instance, the strategical phase concerns the capacity of stabling and servicing rolling stock. Then, the tactical planning happens within several months until 2 years in advance. Here, the previous determined capacity demand and restrictions are used for creating the timetable, the rolling stock plan and the node plan. In the operational planning phase, the timetable and rolling stock plan are executed as well as possible; in case of any disturbances, the aim is to minimise the impact on both plans. This requires flexibility of the node plan because it may entail train units to be taken out of or provided to the network. Another need for flexibility of the node plan is the uncertainty of service tasks to be performed: since the rolling stock plan may change during the day (due to small or large 'disturbances') it is uncertain which train units end at which service locations; hence, the service needs remain uncertain.

Not only do the finalised planning components show the same level of detail, but also the different planning phases are all planned to an exactness of ten seconds.

Plan products

There are two long-term plan products which are developed in the strategical planning phase, namely the *"Materieel Park Plan"* (MPP) and *"Materieel Inzet Plan"* (MIP). The MPP comprises all available rolling stock of NS and specifies what rolling stock is required. The MIP contains information about the rolling stock type per train series (e.g. Sprinter type *SNG* mainly drives in the Randstad and Sprinter type *Flirt* drives in the Southern part of the Netherlands) and the service locations at which the trains end. These two plan products present input for the plan products of the tactical planning phase.

The tactical planning phase comprises several plan products (i.e. BD, BDU and SD). The *"Basic Day"* (BD) plan is generic for the entire year (but for each weekday separately) and is required to request the required paths at the infrastructure manager (ProRail). In the subsequent plan products *"Basic Day Update"* (BDU) and *"Specific Day"* (SD), the timetable and rolling stock is customised to a smaller range of days. While a BDU applies to about 2 months, an SD applies to 1 specific day. Customisation is required because of, for instance, demand fluctuations and track maintenance, which both can apply to a specific day (e.g. events and small maintenance jobs) or a longer time period (e.g. the busy month of September, and large maintenance projects). These updated plans are also requested at the infrastructure manager.

In order to determine the feasibility of the timetable and rolling stock planning for the nodes, currently the entire node planning is completed. The node planning is currently done manually with very little technical support, making it inefficient. Technical support is being developed which uses the BC planning tool as a core. In the BD, BDU and SD phase, the node plan has two purposes: in addition

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[13] Note that the BC is not used for the planning yet.

to the feasibility check mentioned above, the node plan provides the required shunting movements which need to be requested at ProRail. Note that at this moment, the service tasks to be performed are not known yet because it is not known which train units will be at which location (i.e. only the material types are known), and every train unit has its own service needs.

Coordination of the plan products with the service locations

Fleuren explains that currently each plan product is forwarded to the service locations. However, the processing of the plan products by the service locations takes mostly too much time in order to directly apply the feedback in the corresponding plan product. Often, adjustments on the BD plan from the side of the service locations can be incorporated in the BDU. As the product plans are updated frequently, only primal reactions from the service locations can be taken into consideration. Certainly, the BD plan is easier to be adjusted for an entire year because there is only one basis week plan. Modifying the year plan within the BDU, on the contrary, would be 6 times as arduous since there are 6 BDUs per year. Hence, this implies higher computational work, which is time consuming and costly.

Recently, the NS tries to make the node planning more integral in order to incorporate the needs and restrictions of stations, service locations and the paths in between. This would facilitate the execution of the feasibility check. By using the integral tool BC, the creation of the complete node plan and the feasibility check can be supported. By means of BC, it is possible to review the plan much faster and also to gain more revealing insights. The tool would allow reviewing multiple scenarios and can thus also evaluate the plan statistically. Therefore, BC may support better adjustments of the rolling stock plan according to what is feasible at a node and what not.

In a future vision, Fleuren indicates that it may also be possible to evaluate multiple scenarios for feasibility on node level before creating a rolling stock plan. In this way, additional specifications could directly be implemented, among others, the maximum number of vehicles and minimum headway. The maximum number of vehicles and minimum headway do also affect each other and interdepend respectively. If the headways are well spread, it is possible to stable more vehicles. These types of interactions are not yet taken into account, but by means of HIP this would be possible.

Restrictions to the planning

Certainly, there are multiple restrictions which have to be considered in the planning. The following list presents examples of limitations for the rolling stock planning:

- Available rolling stock (i.e. number of rolling stock units per rolling stock type)
- Availability of rolling stock units per time and location
- Allowed train compositions
- Required passenger capacity (i.e. passenger demand)
- Minimum headway of successive trains (5 minutes is mostly taken as minimum headway.
  However, it could already be too short in order to allow shunting.
  Normally, 10 minutes is considered as a perfect headway between two successive trains.)
- Maximum number of rail wagons per train (dependent on capacity of platform)
- Number of rail wagons added to and/ or removed from a train (dependent on headway restrictions)
- Minimum turning times
- Balance between amount of arriving and departing rolling stock units at a service location

Also the service planning has multiple restrictions as indicated below:

- Service frequencies per rolling stock type per service
- Service capacity per service location
- Stabling capacity per service location
- Required service demand
- Accessibility of service location (dependent on number of access paths and traffic)

A.4. Alexander van Wersch (DB Regio), 12 July 2019

Van Wersch is the head of the business area of vehicle management at DB Regional northern Bavaria. He ensures that the rail vehicles are in line with the economy, quality, reliability and customer requirements.

Besides, he is responsible for the assignment and planning of the maintenance, cleaning and procurement of the rail vehicles.

DB Regional vs. DB Long-Distance

Deutsche Bahn (DB) differentiates between DB Long-Distance (i.e. long-distance railway) and DB Regional (i.e. regional-distance railway). While the ICE and IC belong to DB Long-Distance, the vehicle fleet of DB Regional consists of RE, RB and S-Bahn. The long-distance railway is a profitable and financially independent company, whereas the regional-distance railway is not profitable and supported by contracting agencies and transport associations. DB Regional Bavaria, for instance, has a contract with the Bayerische Eisenbahngesellschaft (BEG), which is the railway authority in Bavaria owned by the state Bavaria. This means that DB Regional Bavaria can decide his own strategy conforming the contract with BEG. Therefore, the DB vision of high frequency train series by 2030 is restricted to DB Long-Distance and has no direct influence on DB Regional.

Service locations of DB Regional

According to Van Wersch multiple tasks are executed on a daily basis at DB Regional, namely small technical checks, interior cleaning and exterior cleaning. Hereby, a small technical check means a short vehicle check executed by the train driver before and after using the vehicle. Such a check is performed at least every 24 hours. For interior cleaning, there are 5 intensity levels, whereby the lowest level is executed every 24 hours and the highest cleaning level is conducted once in 6 weeks. The frequency of the exterior cleaning is once per week. All these tasks are performed at a stabling or service location close to the station. Maintenance tasks and larger technical checks are executed by another department at a different location. Even though DB Long-Distance holds own service locations, requests for stabling and servicing ICEs and ICs can be received by DB Regional. In case there is sufficient capacity, DB Regional accepts those requests. In Nürnberg, for instance, long-distance rail vehicles can also be serviced.

DB Regional northern Bavaria owns three service locations: in Nürnberg, Würzburg and Hof. However, trains can also be stabled at night at cleaning stages and parking places of the mobility network. The lowest interior cleaning level can, for example, also be executed at the stabling location in Bamberg, which enlarges the stabling and service capacity of the service locations. Nürnberg, Würzburg and Bamberg also form an important triangle for the train series as can be seen in Figure A.1.

Figure A.1: Service and stabling locations of DB Regio northern Bavaria

The busiest period at the service locations is the night as the majority of rail vehicles needs to be cleaned at night. This is based on the low availability of vehicles for daytime cleaning due to being in operation during daytime. The lowest cleaning level tasks with 24 hour frequency, for instance, always happen at night. However, rail vehicles are also taken out of operation in order to conduct larger cleaning works during daytime. Per service location there is only one exterior cleaning facility. Therefore, the availability of the cleaning facility is also a factor influencing the time period of executing cleaning works.

The vehicle circulation is not scheduled in a way such that each specific vehicle ends up at the same service location every day. Just on the day of operation the vehicles are allocated towards a service location. Hereby, the natural destination of a vehicle is taken into account. The vehicles of a train ending up in Nürnberg, for instance, should be allocated to the service location in Nürnberg. In case of a vehicle disruption or severe soiling, vehicles are also taken out of the planned vehicle circulation. Here, vehicles in reserve may be used or other vehicle circulations are adjusted in order to ensure sufficient transport capacity.

Capacity issues at service locations of DB Regional

Depending on the work intensity, the occupancy rate of different tasks varies. Special cleaning, such as removing graffiti or intense toilet cleanings are very time consuming and thus often near full capacity. Besides, the exterior cleaning faces capacity issues due to the low availability of cleaning facilities. These capacity issues are only visible at night when trains are not in operation. At DB Regional, there are no physical capacity issues as vehicles can be stabled outside of the service locations (e.g. at the stabling location in Bamberg).

As already mentioned disruptions can be caused by means of a malfunction of the rolling stock. In such a case an additional vehicle should replace the disrupted vehicle. This may not always be possible; however, meeting the requirements of the timetable has higher priority than the cleanliness of the vehicles. Large cleaning works, for instance, might be removed for a higher purpose of a vehicle.

Solving capacity issues at service locations of DB Regional

Van Wersch explains that DB Regional is already expanding the infrastructure of the cleansing platforms. With respect to the exterior cleaning, DB Regional tries to use the cleaning facilities also during daytime and if necessary switches to other facilities (of other service locations).

According to Van Wersch, the main potential of increasing the capacity of service locations is to maximise the usage of service locations. This means that they should be used also during daytime. At DB Regional the service locations are already used during daytime, however, only to a certain extent depending on the vehicle availability. From an economical perspective, a maximum vehicle usage is required. This mostly represents the highest priority as mentioned before.

Van Wersch thinks that a rolling stock exchanging concept might be feasible, yet not desirable. He justifies this by explaining that such a rolling stock exchanging system would be very work intensive due to driving each exchanged vehicle forth and back to a service location. For these trips to and from the service locations an additional train driver will be required. Furthermore, the maximum waiting time of a train is 6 minutes. Often it is only 2 minutes. As the stations are through stations, the train drivers do not even have to walk to the other end of the station. Coupling and decoupling rolling stock units, however, would require additional time. According to Van Wersch, such a rolling stock exchanging concept would need to be well planned. Nevertheless, it is not preferable to make a complete plan on vehicle level already in advance. This would be too elaborate and not predictable enough as vehicles are frequently employed in a flexible way.

A.5. Marieke Schemmekes & Wietske van Heusden (NS), 25 July 2019

Schemmekes is the team manager at the regional control centre (RBC) of the southern Netherlands region. Van Heusden is the team manager of the department Voorbereiden & Bijstellen (i.e. Planning & Adjusting) of the southern and western region and is responsible for creating the specific day (SD) plan.

Planning system

Van Heusden explains that three weeks in advance the specific day (SD) plan is created. This plan is not been modified within the last three weeks before the day of operation except when it concerns safety or social importance. In case of short-term requests, the SD plan can sometimes not be completed, so the RS controllers need to be informed and operationally adjust the plan. Generally, the RS controllers try to comply with the plan. In case of a disruption, they need to find a solution that minimises the deviation from the plan and subsequently restore the plan.

Taking an RS unit out of its circulation

According to Schemmekes it happens multiple times per day that rolling stock units need to be taken out of the planned rolling stock circulation. Reasons for this can be a technical disruption of the train unit concerning the train safety, but also, for instance, a breakdown of the air conditioning on a hot day making it unacceptable for passengers to stay on the train.

The process of taking a rolling stock unit out of its circulation looks as follows: First, the machinist of the disrupted train calls the rolling stock planner (i.e. MBN planner) at the national control centre (LBC) informing him about the issue. Then, the MBN planner tries to find a service location close to the site of the disrupted train and checks whether the service or maintenance location is available. Then, he communicates with the national rolling stock controller, who has an overview about all trains within the Dutch railway network. Subsequently, the national rolling stock controller sends a request towards the local rolling stock controller of the specific node. The local rolling stock controller of the specific node needs to analyse whether there is an access path towards the service location, whether a train driver is available for shunting the train and whether there is actually space at the service location. In case there is no obstacle, the local controller organises the removement of the disrupted train. In case there is an obstacle, he declines the request of the national controller by describing the obstacle or pointing out a different moment in time when the removement will be possible. Subsequently, the national controller tries to figure out another solution by eliminating the obstacle, accepting the postponed removement or finding another service location. The above described process is visualised in Figure A.2.

Cooperation between service locations and rolling stock controllers

Schemmekes and Van Heusden outline the different objectives of service locations and rolling stock planners. While the main objective of the service locations is to provide fully functional and clean rolling stock units, the rolling stock planners need to ensure that the right train is at the right moment at the right location available for operation. Due to these partly competing objectives, the cooperation of the rolling stock planners and controllers with the maintenance and service locations is often difficult. The service locations, for instance, try to get specific rolling stock units, which require service. Hence, they request the rolling stock controllers to get those specific rolling stock units out of the circulation. For the rolling stock controllers, however, the first priority is to comply with the timetable and the second priority is to maintain the right train compositions. For the right train compositions only the RS types play an important role, yet not the specific RS units. Only in case of an acute problem (e.g. a safety issue), a rolling stock unit is directly taken out of the circulation. Otherwise, RS controllers try to send the RS unit at the end of the operational day towards a service location. In case of a lack in available rolling stock, the cleaning deadlines are the first being postponed.

Servicing trains during daytime

Schemmekes explains that in Eindhoven the physical capacity is fully used at night. If everything goes according to plan, it fits perfectly. However, unplanned shunting or stabling additional rolling stock units are not or almost not possible. As described before, interruptions happen on a daily basis, so the operations do hardly ever stick to the plan. An increase in capacity is thus highly necessary.

Van Heusden sees high potential in servicing trains during daytime as there are many rolling stock units out of operation between the morning and evening peak (i.e. between 9:30 and 15:00). However, she says that a good planning will be required. She thinks that the concept of a rolling stock exchange may be possible, yet not directly implementable. Van Heusden says that small steps have to be taken until this concept can be implemented. According to her, the rolling stock units, which are out of operation during the peak hours, should be cleaned during daytime already.

A.6. Michel Fokkenrood & Erik Gerritzen (NS), 9 September 2019

Fokkenrood and Gerritzen are national rolling stock controllers at the national control centre (LBC) of NS in Utrecht. National rolling stock controllers have the overview about all trains circulating in the Dutch network.

Taking an RS unit out of its circulation

At the LBC, there are multiple teams that need to coordinate frequently (see Figure A.2). In case an RS unit has a defect, there are mainly four teams involved: the rolling stock management for maintenance and service (*MBN: Materieel Besturingscentrum Nederland*), the national RS controllers (*Dutch: Materieelregelaars*), the team of national monitoring rolling stock (*LMM: Landelijk Monitor Materieel*) and the team of national monitoring personnel (*LMP: Landelijk Monitor Personeel*). First, the MBN planners get informed by the train driver about the defected RS unit. Subsequently, they coordinate with a service location or a maintenance location to ask whether they have capacities to repair the RS unit. Note that within the MBN team, there is one planner for the service locations and one for the maintenance locations. Then, they send a request towards the national RS controllers in order to get the defect RS unit out of the circulation. The national RS controllers coordinate with the LMM employee, who can check where and what RS is available and also evaluate priorities. Sometimes, the need for reparation is not that urgent and it is sufficient if the RS unit visits the SL after operations (i.e. in the evening). Also, they can estimate the duration of a reparation and thus indicate at what moment in time the RS unit will be available for operations again. Then, the national RS controllers send a request towards the local RS controllers, who have a more detailed view of their area. The local RS controllers can, for instance, see whether there is an available path towards the service location. Moreover, the team of the LMP monitors the train drivers and checks their availability in order to solve the removal of the disrupted train and the onward journey of the planned trip. Note that a conductor is not necessary if no passengers are transported. In general, the MBN team is controlling the technical part of a disruption, whereas the RS controllers are solving the logistical challenges.

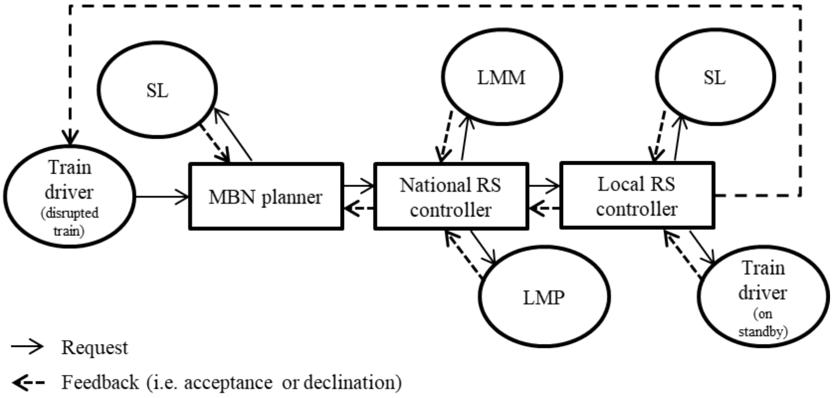


Figure A.2: Coordination between RS controllers and service locations in case of a disrupted train

Servicing trains during daytime

Fokkenrood and Gerritzen see both potential and obstacles with respect to daytime servicing. On the one side, there are multiple spaces in the RS circulation, which may allow daytime servicing. On the other side, these spaces are frequently used as buffer in case of a disruption. If a train is defect, RS units standing on reserve at an SL can directly be put into operations. This is very convenient in order to run as fast as possible again according to the plan. In case of planned daytime servicing, additional RS units would be necessary to ensure such a buffer or the planned daytime servicing would need to be skipped.

According to the national RS controllers also a large number of additional train drivers will be needed when implementing the RS exchange concept. They remarked that due to large walking distances, train drivers would be for a long time out of service after bringing an RS unit towards an SL. Furthermore, additional cleaning personnel would need to be hired for daytime servicing. As the current service capacity at night is almost fully utilised, it will not be sufficient to just shift current night employees towards the daytime shift.

A.7. Anonymous (NS), 12 September 2019

As the interviewee prefers to stay anonymous, *'NS worker'* is used instead of his real name. The NS worker works at the service location in Eindhoven and is very familiar with the processes, problems and needs for improvements at the service location.

Service Planning

The NS worker indicates that they currently work mainly with two planning systems which are not connected with each other. On the one hand, they use "Maximo" as planning system. Maximo contains the BDU plan in order to create work orders. These work orders need to get approved by the work planners. The work planners enter a "yes" or "ok" or check off a task. Then, they need to enter the name of a technician or train driver to whom the task is assigned to. Subsequently, Maximo sends a work order towards the assigned blue colour worker. Note that in case of an interior cleaning task, the external cleaning company Hago is managing the task assignment. The NS worker and his team do not have the control of the interior cleaning execution. The work order created by Maximo indicates what type of cleaning should be performed at which RS unit; however, it does not say where and when the task has to be executed. Hence, the blue colour workers need to make their own working schedule. The duration of a task may vary not only between different types of RS, but also between different RS units of the same type. This is due to different states of the RS units based on their previous executed service, their utilisation and age.

On the other hand, the work planners manually create a daily service plan in Excel, which involves the requests from the SD plan. Note that the BDU plan is a basic week plan for 8 weeks and significantly differs from the SD plan, which is the plan for the specific day. This Excel plan presents the current and the forecasted service planning from a specific moment in time. Every 8 hours (i.e. three times per day) such a planning snapshot is created. Even though urgent service requests occur on a daily basis, these updates are not implemented in the most recent Excel plan.

As the planning system Maximo and the Excel plan are not connected with each other, there is need of manually entering data, which takes a large amount of time. Instead of regular updates, they only make an overview of three time moments per day. Moreover, the visualisation of this overview is unsatisfactory. Therefore, the NS worker and his team are looking forward to the new project called *'SLIM'*. SLIM stands for *'systeem logistieke inzet materieel'* and describes a system that handles the logistical RS usage. SLIM is still in its development phase, but it should be tested in about 5 weeks from now. This system uses the planning system Maximo by automatically entering the data of the SD plan from Donna. As the SD plan is already completed 56 hours in advance, the service planning can also be prepared 3 days in advance. All adaptations to the SD plan are directly updated in SLIM. The advantage of SLIM is also that it indicates the place and the time span of the requested service task. Furthermore, SLIM has a great visualised overview.

Interior cleaning tasks

The NS worker explains that interior cleaning happens every day, however the individual cleaning tasks vary in frequency. The emptying of bins, for instance, happens at least once per day and is also performed at turning stations during daytime (*Dutch: keerpuntreiniging*). More effortful cleaning tasks are only performed at night at SLs. While toilets are also cleaned every day, the floor is cleaned twice per week and windows once per week. Currently, there is a national plan indicating at which days which interior cleaning tasks need to be performed. Hence, it does not matter if an RS unit ends up at a different SL as the same cleaning tasks are executed at all SLs. However, if an RS unit skips, for instance, the window cleaning due to disturbances and deviations from the plan, the RS unit would need to be taken out of its circulation during daytime leading to additional deviations from the plan. Otherwise, the windows of that RS unit are not cleaned for a period of 2 weeks.

NS signed a contract with the interior cleaning company Hago saying that at least 70% of all RS units need to be spotless cleaned while the remaining 30% may be less clean if the time is not sufficient. According to the NS worker this agreement is difficult to check as nobody from NS controls the interior cleaning. Even though an RS unit stood already clean at the SL for the entire day and was not cleaned in the specific night, Hago can count that RS unit as one of the spotless cleaned RS units.

Furthermore, the NS worker says that passengers expect trains to have at least a primary purification. This is not the case at the moment, yet from January 2020 the interior cleaning system changes. The new system entails a primary purification for all RS units and individually adds cleaning tasks to RS units based on urgency. The NS worker is in favour of this new system as he expects trains to be cleaner than nowadays.

Servicing trains during daytime

According to the NS worker the main capacity issue is the lack in physical stabling capacity. This problem will not be solved by servicing during daytime because the serviced RS units still need to be stabled anywhere at night. Nowadays, RS units are frequently assigned to other SLs due to a lack in stabling capacity at Eindhoven. Therefore, many empty kilometres are made as RS units drive empty from Eindhoven towards other locations in the evening and return empty in the morning in order to operate from its starting point in Eindhoven.

In case a higher service demand is planned in advance, the SL can hire additional personnel. According to the NS worker, there is no lack in personnel. However, due to a lack in communication and cooperation between the SD planners and the SLs as well as due to unforeseen work intensities per RS unit, it is possible that not all RS units can be fully serviced during the night shift. Therefore, so-called “dirty starters” occur, which need to be taken out of their circulation during the day in order to get cleaned.

Although there is no lack in personnel, there is need for daytime servicing. This is due to the fact that an employee must not only work at night as regulated by law. Hence, there are approximately 2 or 3 technicians and also 2 train drivers at the SL during daytime waiting to service and shunt RS units. Currently, there are only a few RS units rolling out during daytime, so blue colour workers are literally searching for work during daytime, whereas at night it is very busy. By law, the more personnel are hired to lower the work pressure at night, the more personnel will also have daytime shifts. In order to make the daytime shifts more efficient, more RS units should be offered for daytime servicing.

RS Exchange Concept

The NS worker is very positive about the idea to increase the number of RS units visiting the SL during daytime as this may lead to more efficient daytime shifts of technicians and train drivers. However, a new problem might occur by randomly exchanging RS units. This problem refers to the maintenance planning of each RS unit, which is planned with respect to a certain number of kilometres or days. The maintenance work is already taken into account in the BDU plan, but if RS units are exchanged, multiple RS units might run more kilometres and others fewer kilometres than actually planned. Hence, the maintenance deadlines may also change. When implementing such an RS exchange concept, it is important to take the adaptation of the maintenance deadline into account.

Moreover, the acceptance of a dirty RS unit is higher in the afternoon than in the morning. According to the NS worker, passengers react more critical towards malodorousness and dirt in the morning than in the afternoon. When considering shifting the night cleaning towards daytime, primary purifications would need to be performed before each train trip in order to please passengers. These primary purifications might be executed at the turning station of a train. This would present a notable change of the current cleaning system, but may increase the passenger satisfaction to a large extent.

B

RS Movements

Experimenting with the RS-SSP Base Model

This section is an addition to Section 5.1.2 as it visualises further scenarios. As opposed to the Base Scenario, Scenario 8 has an objective function of 10 RS units having completed servicing. Figure B.1 shows that RS unit 13 is continuously in operation and never enters the SL. Due to the minimum required servicing duration of 3 hours, there is not sufficient time for all RS units to be serviced. RS unit 8 is the first RS unit which can be exchanged because RS unit 15 has completed servicing. RS unit 8 is not ready to be exchanged with RS unit 13 before 15:06. The remaining time within the time horizon does thus not allow RS unit 13 to complete servicing anymore. In addition, RS units can only enter the SL when it arrives at Zwolle station.

In Figure B.2a an additional RS unit (i.e. RS unit 4 as highlighted yellow) is initially standing at the SL as compared to the Base Scenario. As all RS units could complete servicing already in the Base Scenario, it is logical that also all RS units can complete servicing with one more RS unit being initially at the SL – as SL^{max} is adapted to SL_0. Furthermore, there is even more buffer time for servicing in Scenario 16 as compared to the Base Scenario.

Figure B.2b visualises the RS movements of Scenario 18 having a train arrival frequency of every hour – as opposed to the 30 minutes headway of the Base Scenario. As only half of the trains are running, also half of the RS units are operating. RS units 13, 2, and 5 are thus not used (as marked in grey). The number of RS units initially standing at the SL is 5 as in the Base Scenario and there is sufficient time for the three remaining operating RS units to be exchanged and serviced within the time horizon.

Figures B.3a and B.3b show Scenarios 22 and 25, respectively. Both scenarios feature train arrival frequencies of every 15 minutes. While Scenario 22 has only 2 RS units initially standing at the SL, Scenario 25 has 8 RS units initially at the SL. Due to this difference, multiple RS units cannot be serviced in Scenario 22, whereas all 20 RS units used for Scenario 25 can complete servicing within the time horizon. Note that reducing SL_0 to 1 led to an infeasible solution.

Model Comparison

This section is an addition to Section 5.2.2. Figure B.4 shows the RS movements for scenarios with a doubled train arrival frequency. The additional number of rows indicate the doubled number of available RS units – i.e. 22 in total. The figure visualises the shortened time horizon of the Base Model as opposed to the previous scenarios starting at 11:21 because of the last RS unit rolling out towards the SL at 11:21.

The longer servicing duration of three hours in Scenario 14 led to fewer RS units visiting the SL as opposed to Scenario 13 featuring a two-hour servicing duration. As the entire time horizon considered by the Base Model is shorter than three hours, no RS exchanges occur in Scenario 14. Only the RS units standing initially at the SL (i.e. the RS units rolling out towards the SL) can complete servicing, in addition to the one entering the SL at 11:21. Note that due to the impossibility of completing servicing of RS unit 6 within the considered time horizon, the RS unit does not even start being serviced.

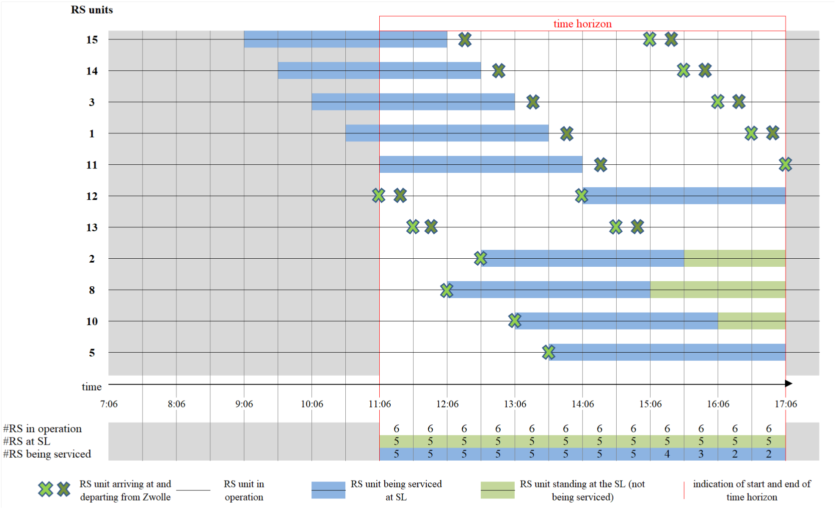
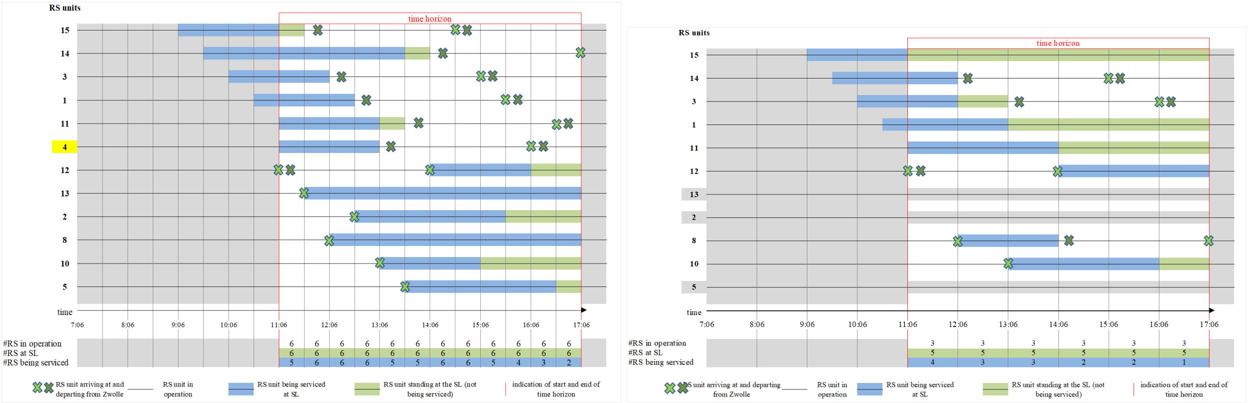
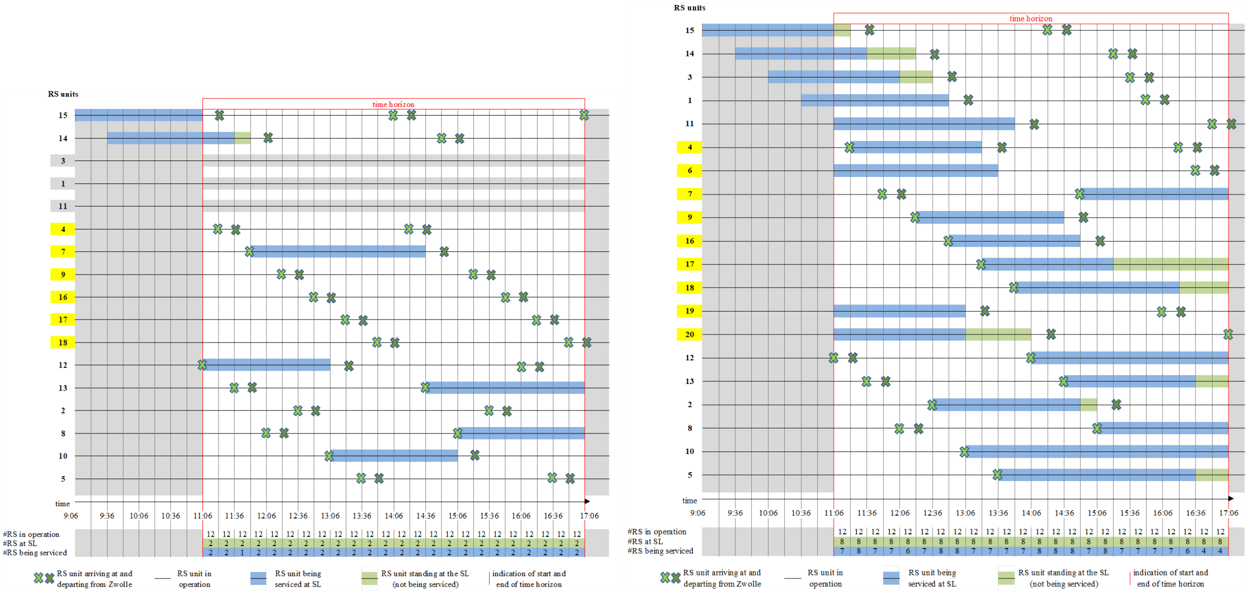


Figure B.1: RS movements – Scenario 8 applied to the RS-SSP Base Model



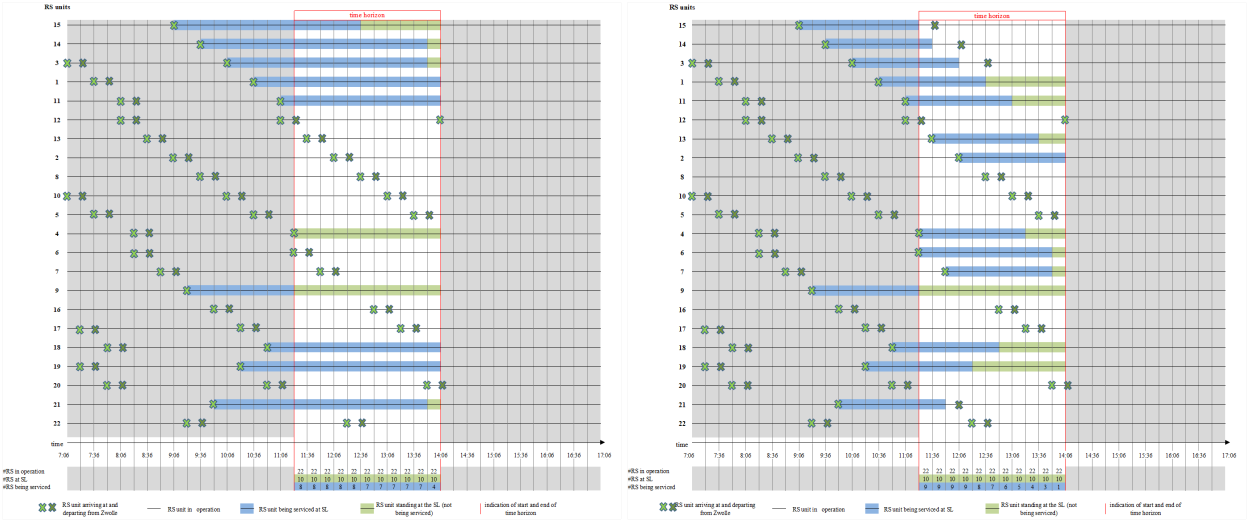
(a) RS movements – Scenario 16 applied to the RS-SSP Base Model (b) RS movements – Scenario 18 applied to the RS-SSP Base Model

Figure B.2: RS movements – Scenarios 16 and 18 applied to the RS-SSP Base Model

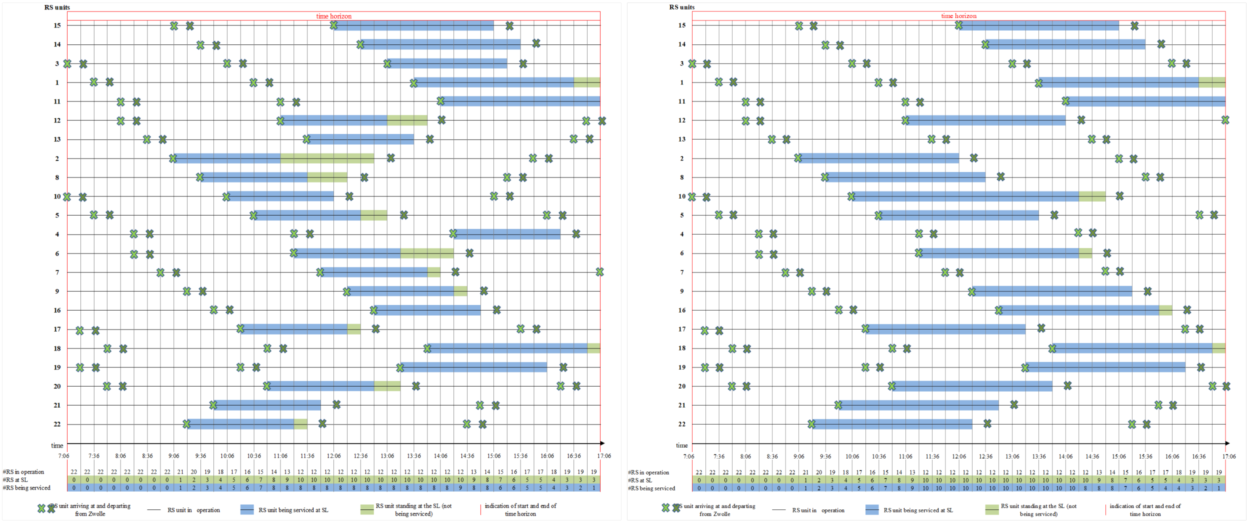


(a) RS movements – Scenario 22 applied to the RS-SSP Base Model (b) RS movements – Scenario 25 applied to the RS-SSP Base Model

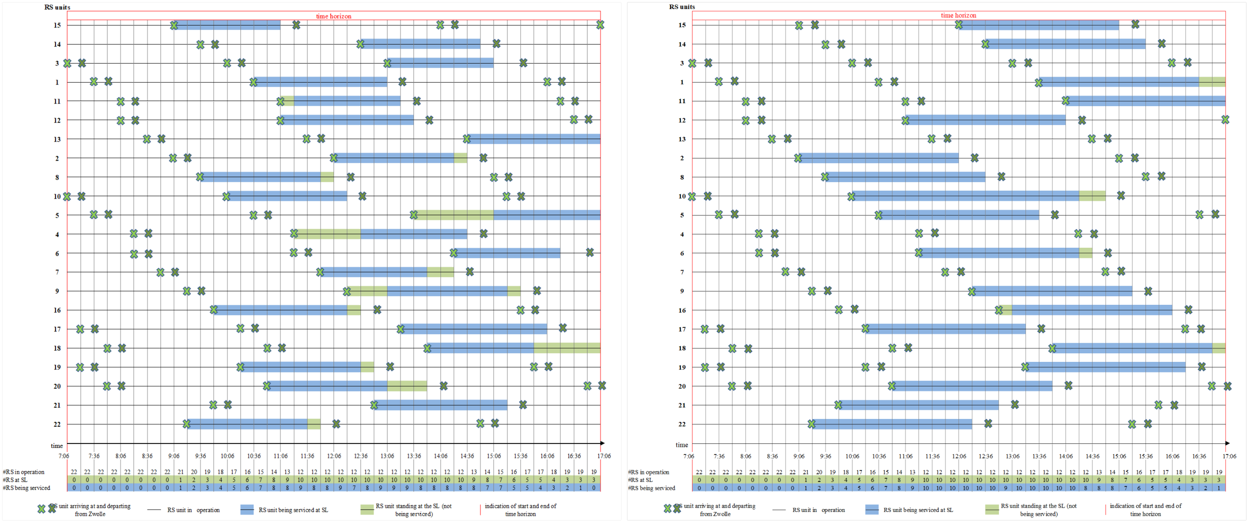
Figure B.3: RS movements – Scenarios 22 and 25 applied to the RS-SSP Base Model



(a) Scenario 13 applied to RS-SSP Base Model (b) Scenario 14 applied to RS-SSP Base Model



(c) Scenario 13 applied to RS-SSP-MU (d) Scenario 14 applied to RS-SSP-MU



(e) Scenario 13 applied to RS-SSP-MU-W (f) Scenario 14 applied to RS-SSP-MU-W

Figure B.4: RS movements – Model comparison with respect to Scenarios 13 and 14

C

Scientific Paper

Increasing the Effectiveness of the Capacity Usage at Rolling Stock Service Locations

M.E.M.A. van Hövell[a,*], Prof. dr. R. M. P.Goverde[a], Dr. N. Bešinović[a], Dr. M. M. de Weerdt[b], Drs. D. M. van de Velde[c], Ir. A. de Groot[d]

[a]*Delft University of Technology. Faculty Of Civil Engineering and Geosciences. Mekelweg 5, 2628 CD Delft, The Netherlands*
[b]*Delft University of Technology. Faculty of Engineering, Mathematics and Computer Science. Van Mourik Broekmanweg 6, 2628 XE Delft, The Netherlands*
[c]*Delft University of Technology. Faculty of Technology, Policy and Management. Jaffalaan 5, 2628 BX Delft, The Netherlands*
[d]*Arcadis Nederland B.V. Piet Mondriaanlaan 26, 3812 GV Amersfoort, The Netherlands*

Abstract

Passengers often complain about dirty trains indicating the relevance of interior cleaning of rolling stock (RS). Servicing tasks (i.e. interior and exterior cleaning and smaller technical checks) are executed on a daily basis at service locations (SLs). Currently, due to train operations during daytime, the current focus lies on night servicing. In this paper daytime servicing is considered in order to tackle the capacity shortages at SLs. Therefore, the Rolling Stock Servicing Scheduling Problem (RS-SSP) is developed comprising a Mixed Integer Linear Programming (MILP) model. By complying with the planned timetable, the RS-SSP maximises the RS units being serviced during daytime. The RS-SSP allows RS exchanges between RS units having completed servicing and operating RS units requiring servicing. Due to this RS Exchange Concept, the number of RS units visiting the SL during daytime can be increased. Within the paper three RS-SSP model versions have been developed: the RS-SSP Base Model and two model extensions. The RS-SSP Base Model considers trains running with a single RS unit per train and RS units to be immediately serviced when entering the SL. The first extension (RS-SSP-MU) considers multiple unit trains and the second extension (RS-SSP-MU-W) allows RS units to wait for servicing. The pro-

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[*] *E-mail address:* madeleinehoevell@gmx.de (M.E.M.A. van Hövell)

posed RS-SSP models have been tested on a real-life case from the Dutch railways. The RS-SSP-MU-W yielded the most feasible and improved solutions as compared to the other two model variants. For multiple scenarios, the model was able to exchange all running RS. As a conclusion, the capacity usage at SLs can be increased by the RS-SSP by shifting the excessive workload to daytime, and thus solving the capacity shortages. As the RS-SSP model is a generic model, it may not only be applied to other railway operators, but also to other public transport companies. Further extensions on the model are suggested for an appropriate applicability on large scale.

Keywords: maintenance routing, daily maintenance, daytime servicing, servicing capacity, rolling stock exchange, decision support model, MILP

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1. Introduction

Rolling stock (RS) is serviced on a daily basis in order to guarantee safety and cleanliness of trains. Servicing comprises minor technical checks, interior and exterior cleaning, and small repairs if necessary. These servicing tasks are mostly executed at service locations (SLs) nearby a station. Currently, RS units are almost exclusively serviced during the evening and night because of operations during daytime (Mo and Sinha, 2014). At the Dutch railway company Nederlandse Spoorwegen (NS), multiple SLs face capacity shortages during the night leading to reallocations of RS units towards other SLs (Grunbauer, 2019). The total servicing demand does not yet exceed the total servicing capacity regarding all SLs of NS. However, NS expects a significant increase in servicing demand due to a larger number of RS units required for introducing higher train frequencies. By 2030 at the latest, the current total capacity of all SLs will be insufficient for servicing all RS units (Topal, 2019). The capacity issue at NS provided an incentive for increasing the effectiveness of the capacity usage at SLs. However, this may also be applicable to multiple other public transport companies (e.g. in the rail, metro, tram, or bus industry).

In order to find a solution for more effectively using the capacity at service locations, the focus is on daytime servicing. It should be remarked that in multiple train series several RS units roll out towards an SL after the morning peak. Those RS units are standing at the SLs waiting for operations in the evening peak. Currently, none of these RS units are fully serviced because they represent insufficient work for employing cleaning personnel during daytime. In this paper we introduce the Rolling Stock Exchange Concept. The idea of the Rolling Stock Exchange Concept is as follows. Firstly, full servicing should be provided to those RS units rolling out towards an SL after the morning peak. Then, as soon as an RS unit completed servicing, it may substitute an operating RS unit arriving at a turning station nearby the SL. By exchanging serviced RS units with servicing requiring RS units, the number of RS units visiting the SL during daytime increases. This leads to a higher workload for servicing personnel making daytime servicing more efficient. Besides, more RS units can complete servicing during daytime. RS units which have completed servicing during daytime will not be serviced at night anymore. Hence, daytime servicing allows to decrease the servicing demand at night. With respect to the current servicing demand, this may solve the capacity issue of individual SLs and avoid RS reallocations. Regarding the expected increase in servicing demand, the total servicing capacity might be sufficient by introducing daytime servicing based on the RS Exchange Concept.

In order to shape the Rolling Stock Exchange Concept, a decision support model is developed, called the Rolling Stock Servicing Scheduling Problem (RS-SSP) model. The RS-SSP model presents a mixed integer linear programming (MILP) model to be used in the tactical planning phase. Its objective is to maximise the number of RS units completing full servicing during daytime while complying with the requirements provided by the planned timetable and from the side of the SLs. The output of the model provides the number of rolling stock units that can be serviced during daytime, and also adjustments of the RS circulation, i.e. which pairs of RS units are exchanged.

The main contributions of the paper are:

1. A new mathematical model RS-SSP for more effectively using the capacity of service locations
2. A new RS exchange concept, providing possibilities of exchanging rolling stock during daytime
3. Considering an RS servicing frequency of once per day
4. Experimental testing of the RS-SSP model on real-life instances of the Dutch railways

The remainder of the paper is organised as follows. First, a literature review is provided in Section 2. In Section 3 the RS-SSP is described and in

Section 4 three RS-SSP model versions are formulated. While computational experiments are described in Section 5, the applicability of the RS-SSP is discussed in Section 6. Finally, the conclusions are given in Section 7.

2. Literature Review

As rolling stock is a valuable and costly asset of railway operators, they need to be well maintained. This means that they regularly need to be cleaned, checked, and repaired if necessary. These tasks are executed at maintenance and service facilities (Huisman et al., 2005).

Due to the complexity and stochastic nature of maintenance, maintenance planning is in practice often executed manually. This is a time-consuming process and leads to non-efficient solutions (Lai et al., 2015). In the past, models have been established with respect to maintenance planning. An example from the aerospace context is the research of Feo and Bard (1989). This study tries to integrate maintenance routing within the flight schedule by minimising costs including maintenance costs. Within the railway sector, the focus on maintenance planning has started later. Sriskandarajah et al. (1998) developed an optimisation model for scheduling large RS maintenance tasks, which incorporated several maintenance planning constraints. Penicka and Bjørner (2004) presented a model solving the RS maintenance routing problem. However, maintenance constraints have not been taken into account for the scheduling problem. Then, Maróti and Kroon (2005) described a transition model for routing trains towards maintenance facilities. For this model, the regular timetable plan and a list of urgent rolling stock units with a maintenance deadline are used as input. The regular plan partly requires adjustment in order to route urgent rolling stock units to a maintenance facility while carrying out timetable services. The same authors (Maróti and Kroon, 2007) present an integer programming model ensuring that urgent rolling stock units reach the maintenance facility in time. The objective of their algorithm is to find the minimal cost flow in the constructed network. Also, Borndörfer et al. (2011) proposed a model for the RS circulation planning taken the cleaning and maintenance time into account. Moreover, Tönissen and Arts (2018) solved an NP-hard maintenance location routing problem by considering the possibility of opening additional facilities, closing facilities, and increasing the facility capacities. They developed a MILP model, which aims to minimise the total annual facility costs. The model allows interchanges between RS units, yet only large maintenance works with an occurrence of once every half year up to every month are taken into account.

According to Giacco et al. (2014), the coordination of maintenance and rolling stock scheduling is still under-investigated. They highlighted the importance of covering services and maintenance tasks within the RS circulation planning with a limited number of rolling stock units. For this problem they developed a model with a two-step approach combining scheduling tasks with respect to train services, short-term maintenance works, and empty runs. Eventually, they applied their model to case studies of the Italian railway company Trenitalia and achieved improvements regarding cost reductions. Lai et al. (2015) developed a model to improve the efficiency in rolling stock usage by optimising the rolling stock assignment and maintenance plan for daily and monthly inspections on operational level. Also, Andrés et al. (2015) defined a detailed maintenance routing model to deal with rapid transit network problems. Therefore, an efficient Bellman-Ford's multilevel algorithm was used for each train type. Both models have taken multiple regulations into account such as train scheduling and maintenance constraints and focus on daily and monthly inspections.

Note that there are also multiple papers in literature addressing the Rolling Stock Rescheduling Problem (RSRP) (e.g. Wagenaar and Kroon (2015)). The RSRP tries to maintain a feasible rolling stock circulation after a disruption has occurred. As a consequence, trains need to be rescheduled. The RSRP differentiate from scheduling problems especially with respect to calculation time requirements. While rescheduling problems need to be solved near real-time and thus require fast calculation times, scheduling problems have less time pressure. Wagenaar and Kroon (2015), for instance, developed three RSRP models based on the Composition model of Fioole et al. (2006), whereas scheduled maintenance appointments are taken into account. In the first model additional rolling stock types are added for RS units requiring maintenance. The second model puts maintenance constraints on maintenance requiring RS units. The third and fastest model creates paths for every rolling stock unit ensuring that RS units requiring maintenance reach a maintenance facility in time. All RSRP models of Wagenaar and Kroon (2015) consider maintenance routing for RS units, which require maintenance at a specific moment in time. This is similar to the maintenance routing models described before. The RS-SSP, however, is more flexible in time and aims to maximise the number of RS units visiting a service location rather than privileging urgent RS units.

Giacco et al. (2014) pointed out that further research is required with respect to limiting the workload for the maintenance operators. Moreover, none of the models consider the efficient usage of the maintenance facilities. Furthermore, the above described models do not incorporate daily RS servicing such as interior cleaning deadlines.

In Table 1 an overview of studies regarding RS planning is given, distinguishing the incorporated aspects (see columns). Also, the RS-SSP model is included in this overview.

	RS related			maintenance related				
	RS allocation	RS circulation	RS interchanges	maint. costs	large maint. works	short-term plan.	daily inspections	daytime cleaning
Huisman et al. (2005)	x							
Abbink et al. (2004)	x							
Alfieri et al. (2006)		x	x					
Peeters and Kroon (2008)		x	x					
Fioole et al. (2006)		x	x					
Haahr et al. (2016)		x	x					
Sriskandarajah et al. (1998)	x				x			
Penicka and Bjørner (2004)		x		x	x			
Maróti and Kroon (2005)		x	x	x	x			
Maróti and Kroon (2007)		x	x	x	x			
Borndörfer et al. (2011)		x	x	x	x			
Tönissen and Arts (2018)		x	x	x	x			
Berthold et al. (2019)		x	x		x			
Giacco et al. (2014)		x	x	x	x	x		
Wagenaar and Kroon (2015)		x		x	x	x		
Lai et al. (2015)		x	x	x			x	
Andrés et al. (2015)		x	x	x			x	
RS-SSP model		x	x				x	x

Table 1: Literature overview regarding RS planning

In literature only a few papers allow changes in the RS circulation plan in order to route urgent RS units to a maintenance facility (see Table 1 "RS interchanges"). In Maróti and Kroon (2005) and Maróti and Kroon (2007), for instance, it is possible to interchange tasks of urgent RS units with non-urgent RS units. However, RS exchanges as proposed in this paper have not been considered in any study before according to the best of the author's knowledge. Furthermore, there are only a limited number of studies considering smaller technical checks with frequencies of approximately 3 times per week. Moreover, none of the existing models take interior cleaning for RS into account, which needs to be executed every 24 hours. This is logical as currently this task is usually performed at night. This type of maintenance routing is, thus, in current RS circulation plans automatically integrated in the evening route plan towards the stabling yard. The model developed in this paper is the first that considers daytime servicing with a 24 hour mean-time between cleaning.

Hence, a decision support model was developed for the Rolling Stock Servicing Scheduling Problem determining which rolling stock units should be exchanged at which time.

3. Problem Description

In order to describe the RS-SSP, Figure 1 visualises the conceptual model.

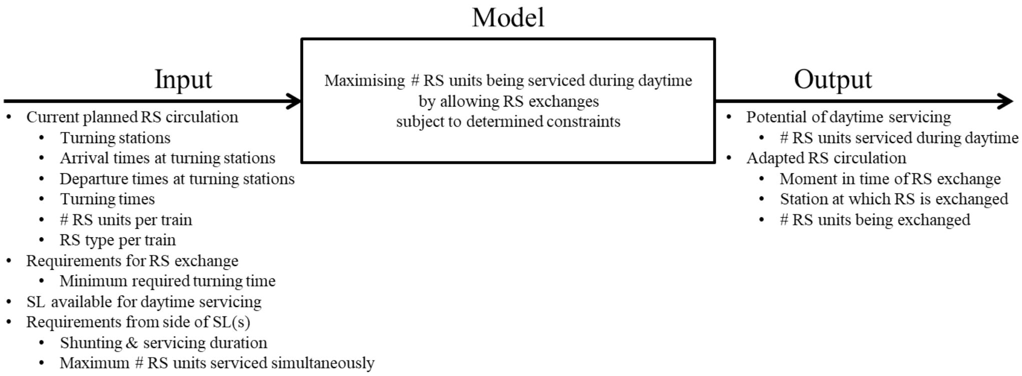

Figure 1: Conceptual model

The input of the model consists of the planned RS circulation, the RS exchange parameters, and SL related information (see Figure 1). Those input parameters are all based on planned data and estimations given by the operator (e.g. NS). The planned RS circulation of NS (NS, 2019) entails the routing of a single RS unit including the turning stations with its arrival and departure times and resultant turning times. As the RS units are assigned to trains, the train compositions with number of RS units and types are given as well. The minimum required turning time for an RS exchange is based on an estimation of Huisman and Zomer (2019). The service locations pose requirements regarding the shunting and servicing duration as well as the maximum number of RS units which can be serviced simultaneously.

Those two requirements are specified per SL (Grunbauer, 2019). The model developed in this paper assumes a single SL to be available for daytime servicing.

The box in Figure 1 contains the mathematical model for solving the RS-SSP. The model consists of the objective function to be optimised (i.e. maximising the number of RS units being serviced during daytime) and the underlying constraints, which need to be met. The RS-SSP model contains multiple functionalities. In contrast to current operations, it allows RS units rolling out towards the SL to be serviced during daytime. Moreover, RS units standing at the SL are not provided for operations unless they have completed servicing. Also, RS exchanges are possible between serviced and servicing requiring RS units. Furthermore, it takes the capacity at the SL into account (i.e. maximum number of RS units, which can be serviced simultaneously) as well as the shunting and servicing duration. Also, the RS-SSP respects the train arrival and departure times given by the timetable and it tracks the RS circulation.

The output of the RS-SSP entails the total number of RS units being serviced during daytime (i.e. objective value) and indicates which RS unit visits the SL at what time.

The functionality of the RS-SSP is further explained by the following example. Table 2 visualises the timetable of a train series[1] arriving at and departing from one turning station. In total 11 RS units are used for operations as indicated by the different colours in Table 2. The cycle time, which is the duration from the moment that a train departs from the turning station until it returns to the same station, is 2 hours and 43 minutes. All trains visible in the timetable of Table 2 feature the same cycle times. The first train arrives at 8:36 and the last train at 17:06. From 9:06 and 11:06 trains arrive with a length of 2 RS units and are decoupled at the turning station. One RS unit is driven towards the SL and the other RS unit runs in the subsequent departing train. In total, 5 RS units are driven to the SL and the remaining 6 RS units keep operating. At 14:53 one of the RS units standing on reserve at the SL is used again for operation. Note that the RS unit circulation as marked in different colours in Table 2 is according to the planned RS circulation (NS, 2019) until the first RS exchange (i.e. beginning with the departing train at 11:53).

Arriving train		**At the SL**	**Departing train**	
# RS units	**Arrival**	**# RS units**	**Departure**	**# RS units**
1	08:36	0	08:53	1
2	09:06	1	09:23	1
2	09:36	2	09:53	1
2	10:06	3	10:23	1
2	10:36	4	10:53	1
2	11:06	5	11:23	1
1	11:36	5	11:53	1
1	12:06	5	12:23	1
1	12:36	5	12:53	1
1	13:06	5	13:23	1
1	13:36	5	13:53	1
1	14:06	5	14:23	1
1	14:36	5	14:53	2
1	15:06	4	15:23	2
1	15:36	3	15:53	2
1	16:06	2	16:23	2
1	16:36	1	16:53	1
1	17:06	1	17:23	1

Table 2: Arrival and departure times at Zwolle according to NS (2019)

As can be seen in Table 2, it is assumed that no RS unit is on reserve at the SL before 08:36. Regarding a shunting and servicing duration of two hours, this means that no RS units are available for exchanges before 11:06. This is because the first RS unit arrives at the SL at 9:06 and is serviced and ready for operation two hours later. Therefore, the period in which RS units can be exchanged starts at the arrival time of 11:06. hours. In the example shown in Figure 2, the first RS exchange occurs at 11:36 even though an RS exchange would have been possible at 11:06. This is because the example shows only one of multiple optimal solutions. Hence, the first RS unit arriving at the SL at 9:06 (marked in light blue) is exchanged with the RS unit arriving at 11:36 (marked in red), the second arriving RS unit (i.e. 9:36 marked in yellow) is ready for an exchange with the RS unit arriving at 12:06 (marked in blue), and so on. There are only 5 RS units rolling out towards the SL after the morning peak and at least 6 RS units are always

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[1] Note that a train series commutes between two turning stations.

in operation simultaneously. In this case, however, it is possible that the RS unit arriving at the SL at 11:36 will be exchanged with the train arriving at 14:06. All 11 RS units can be serviced during daytime according to the schedule presented in Table 2.

4. Rolling Stock Servicing Scheduling Problem

In total, three RS-SSP model versions have been developed: the RS-SSP Base Model, the RS-SSP with Multiple Units (i.e. RS-SSP-MU), and the RS-SSP-MU with Waiting for servicing (i.e. RS-SSP-MU-W). Note that the RS-SSP-MU is an extension of the Base Model and the RS-SSP-MU-W is an extended version of the RS-SSP-MU. While the Base Model assumes that trains run with a length of one RS unit, the two model extensions allow trains to run with multiple RS units. The RS-SSP Base Model and the RS-SSP-MU assume that an RS entering the SL starts servicing immediately. The RS-SSP-MU-W, in contrast, allows RS units to wait at the SL for being serviced.

4.1. Model Components

The Base Model of the RS-SSP is based on multiple assumptions. Those assumptions are summarised in the list below:

- 1 single day
- 1 single service location
- 1 single RS type
- 1 single RS unit per train
- Trains are not (de-)coupled during their cycle time
- RS units start servicing immediately when entering the SL

Table 3 defines the model components for the RS-SSP. A detailed description could be found in Van Hövell (2019).

Sets		
I	set of train arrivals	
K^{arr}	set of arriving trains	
K^{arr_0}	set of first arriving trains not having a predecessor	
K^{dep}	set of departing trains	
RS	set of all RS units	
RS^{SL_0}	set of RS units standing initially at the SL	
Indices		
i	phase between train arrivals	$i \in I$
k	arriving train	$k \in K^{arr}$
l	departing train	$l \in K^{dep}$
u	RS unit requiring service	$u \in RS$
Input parameters		
τ_k^{arr}	arrival time of train k	[hh:min]
$\sigma(l)$	returning train of train l	
$arr(i)$	arriving train in phase i	
$dep(i)$	departing train in phase i	
tt_k	turning time of train k	[hh:min]
tt^{min}	min required turning time for exchanging RS units	[hh:min]
RS_k^{nr}	number of RS units in train k	
RS_k^{spec}	specific RS unit running in train k	
T_u^{in}	moment in time at which RS unit u entered the SL	[hh:min]
SL_0	number of RS units initially in service at the SL	
SL^{max}	max possible number of RS units serviced at the SL simultaneously	
d^{max}	maximum shunting and service duration	[hh:min]
Decision variables		
$y_{u,i}$	= 1 if RS unit u visits the SL at the start of phase i, 0 otherwise	$y_{u,i} \in \{0,1\}$
$y'_{u,i}$	= 1 if RS unit u leaves the SL at the start of phase i, 0 otherwise	$y'_{u,i} \in \{0,1\}$
$z_{u,i}$	= 1 if RS unit u starts being serviced at the start of phase i, 0 otherwise	$z_{u,i} \in \{0,1\}$
$z'_{u,i}$	= 1 if RS unit u completed servicing at the start of phase i, 0 otherwise	$z'_{u,i} \in \{0,1\}$
Auxiliary variables		
$x_{u,k}$	= 1 if RS unit u runs in train k, 0 otherwise	$x_{u,k} \in \{0,1\}$
u_i	number of RS units in service at the SL at the start of phase i	$u_i \in \mathbb{Z}_0^+$

Table 3: Model components

The RS-SSP model entails multiple binary decision variables. The decision variable $y_{u,i}$ represents whether an RS unit u visits the SL at the start of phase i. $y'_{u,i}$ indicates whether an RS unit u leaves the SL at the start of phase i. Furthermore, the decision variable $z'_{u,i}$ states whether an RS unit u completed servicing at the start of phase i. In addition, the model also uses two auxiliary variables. The binary variable $x_{u,k}$ represents whether an RS unit u runs in train k and u_i counts the number of RS units being serviced at the SL at the start of phase i.

In Figure 2 the decisions to be taken at the turning station are visualised, including the resulting RS movements. All variables are located at an arc or node within the figure. The figure shows a turning station consisting of four different nodes. The arrival (arr) at and the departure (dep) from the turning station represent the lower two nodes. The service location is represented by the upper two nodes, whereas the left one (u_i) counts all RS units which are being serviced in phase i. The right node is the assembling place for all RS units which have completed servicing. The arcs show how an RS unit may get from one to the other node. Starting from the arrival node, an RS unit u has two possibilities. In the case that $y_{u,i} = 0$, the RS unit u goes towards the departure node in order to run in the next departing train (i.e. $dep(i)$). In the case that $y_{u,i} = 1$, the RS unit goes towards the SL. In the RS-SSP Base Model it is assumed that each RS unit arriving at the SL can be serviced immediately after its arrival. Hence, the service duration starts at the moment at which the RS unit arrives at the SL. Assuming that the service duration lasts m phases, the RS unit u completes servicing in phase $i + m$. This means that the binary decision variable $z'_{u,i+m} = 1$ and that the RS unit u is subtracted from the assembly u_{i+m}. From the moment that the RS unit u completed servicing, it is available for an RS exchange. Therefore, at a phase $i + n$, where $n \geq m$, the decision variable $y'_{u,i+n}$ may turn 1. This means that the RS unit u leaves the SL and goes to the departing node in order to run in the next departing train ($dep(i + n)$). The variable $x_{u,l}$ indicates whether an RS unit u runs in the departing train l (i.e. $x_{u,l} = 1$) or not (i.e. $x_{u,l} = 0$). Note that the index i is used in order to keep track of the phase in time. This is mainly important for tracing the RS circulation. If train k, for instance, arrives in phase i (i.e. $k = arr(i)$) and RS unit u runs in train k ($x_{u,k} = 1$), then the RS unit u may either run in train l departing in the same phase i (i.e. $x_{u,l} = 1$ with $dep(i) = l$) or enter the SL.

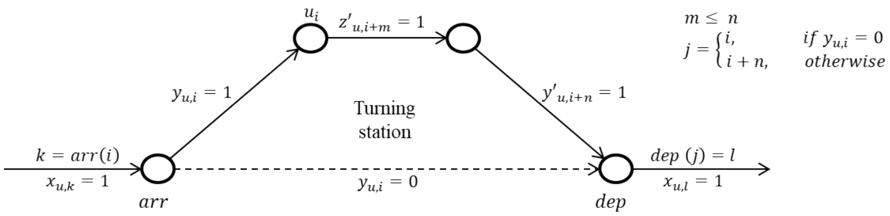

Figure 2: Decisions at the turning station

4.2. RS-SSP Base Model

The RS-SSP Base Model is formulated as follows.

$$maximise \sum_{u \in RS} \sum_{i \in I} z'_{u,i} \tag{1}$$

subject to

$$y_{u,0} = 1\ \forall u \in RS^{SL_0} \tag{2}$$

$$\sum_{u \in RS} y_{u,0} = SL_0 \tag{3}$$

$$x_{RS_k^{spec},k} = 1\ \forall k \in K^{arr_0} \tag{4}$$

$$u_0 = z'_{u,0} = y'_{u,0} = 0\ \forall u \in RS \tag{5}$$

$$u_{i+1} = u_i + \sum_{u \in RS} y_{u,i} - \sum_{u \in RS} z'_{u,i}\ \forall i \in I \tag{6}$$

$$u_i \leq SL^{max}\ \forall i \in I \tag{7}$$

$$y_{u,i} \leq x_{u,arr(i)}\ \forall u \in RS, i \in I \setminus \{0\} \tag{8}$$

$$x_{u,dep(i)} = y'_{u,i} + x_{u,arr(i)} - y_{u,i}\ \forall u \in RS, i \in I \tag{9}$$

$$x_{u,\sigma(l)} = x_{u,l}\ \forall u \in RS,\ \forall l \in K^{dep} \tag{10}$$

$$\sum_{u \in RS} x_{u,k} = 1\ \forall k \in K^{arr} \tag{11}$$

$$y_{u,i} \cdot tt^{min} \leq tt_{arr(i)}\ \forall u \in RS, i \in I \setminus \{0\} \tag{12}$$

$$z'_{u,i} \cdot d^{max} \leq (\tau^{arr}_{arr(i)} - T^{in}_{u}) \; \forall u \in RS^{SL_0}, i \in I \tag{13}$$

$$z'_{u,i} \cdot d^{max} \leq (\tau^{arr}_{arr(i)} - \sum_{j=0}^{i} (y_{u,j} \cdot \tau^{arr}_{arr(j)})) \; \forall u \in RS \setminus RS^{SL_0}, i \in I \tag{14}$$

$$z'_{u,i} \leq \sum_{j=0}^{i} y_{u,j} \; \forall u \in RS, i \in I \tag{15}$$

$$y'_{u,i} \leq \sum_{j=0}^{i+1} z'_{u,j} \; \forall u \in RS, i \in I \tag{16}$$

$$\sum_{i \in I} y_{u,i} \leq 1 \; \forall u \in RS \tag{17}$$

$$\sum_{i \in I} y'_{u,i} \leq 1 \; \forall u \in RS \tag{18}$$

$$\sum_{i \in I} z'_{u,i} \leq 1 \; \forall u \in RS \tag{19}$$

$$\sum_{u \in RS} y_{u,i} = \sum_{u \in RS} y'_{u,i} \; \forall i \in I \setminus \{0\} \tag{20}$$

Equation (1) presents the objective function, which maximises the total number of rolling stock units which completed servicing during daytime. It is assumed that all rolling stock units are in operation at peak hours, so daytime servicing is only possible at off-peak hours between the morning and evening peak.

Constraint (2) sets the initial decision variable $y_{u,0}$ to 1 for those RS units which are initially standing at the SL. Constraint (3) sets $y_{u,0}$ to 0 for all the remaining RS units. Furthermore, Equation (4) ensures that for the first arriving trains without a predecessor train for which the RS circulation is already known all $x_{u,k}$ are 1 if RS unit u runs in train k, 0 otherwise. Constraint (5) sets all remaining variables of phase $i = 0$ to zero.

Equation (6) tracks the number of RS units being in service in phase $i+1$ by adding the number of RS units visiting the SL in phase i and subtracting the number of RS units which completed their service at the SL in phase i

by the number of RS units being in service at the SL in phase i.

Constraint (7) ensures that the number of RS units being in service at the SL does not exceed the maximum number of RS units which can be serviced simultaneously during daytime at the SL (i.e. SL^{max}). Furthermore, an RS unit can only enter the SL in phase i if that RS unit runs in the train arriving in phase i. This constraint is formulated in the Equation (8).

Equation (9) states that the RS unit running in the train departing in phase i is either the same as the RS unit leaving the SL in phase i or the RS unit which arrived in phase i. Note that in case of each of these scenarios, the other scenario is not applying.

Furthermore, the train composition does not change within the cycle time of a train. Thus, the same RS units are running in train l as in its returning train $\sigma(l)$. This is formulated in Equation (10). Equation (11) ensures that one RS unit is running in each scheduled train. This is according to the assumption that each train runs with a single RS unit. Constraint (12) guarantees that RS units can only be exchanged if the turning time of the arriving train exceeds the minimum turning time. Constraints (13) and (14) track that $z'_{u,i}$ is only 1 if an RS unit u has been in the SL for a duration of the maximum service and shunting time (i.e. d^{max}). Constraint (13) focuses on the RS units which are initially standing at the SL and thus have an entering time T^{in} prior to the arrival time of the first arriving train. Therefore, $\tau^{arr}_{arr(i)} - T^{in}_{u}$ is always positive. Constraint (14), on the contrary, considers the RS units which are not initially standing at the SL. In order to avoid negative values on the right side of the Equation, the length of stay at the SL is only observed of those RS units which have been standing at the SL before or in phase i. By means of Constraint (15), it is ensured that an RS unit can only be serviced in case it entered the SL. Without Constraint (15), $z'_{u,i}$ might turn one according to Constraint (14) for RS units which have never entered the SL. It might be worth mentioning that although $z'_{u,i}$ could always be zero according to Constraints (13) and (14), this will not happen as the objective function maximises the number of RS units which completed servicing.

With Constraint (16), it is ensured that an RS unit u only leaves the SL in case it has been fully serviced. Furthermore, RS units must not visit or leave the SL multiple times per day. Hence, Constraint (17) avoids that an RS unit u visits the SL more than once during the same day and Constraint (18) ensures that each RS unit leaves the SL at most once. In addition, Constraint (19) guarantees that no double servicing is done. And finally, Constraint (20) ensures that an RS unit can only enter the SL if another RS unit leaves the SL in the same phase.

4.3. RS-SSP with Multiple Units

In this section, an extension is made to the Base Model. The RS-SSP Multiple Units (RS-SSP-MU) enables trains to run with a length of multiple RS units.

The RS-SSP Base Model assumed that all trains run with a length of one RS unit. In reality, however, trains often run with multiple RS units. Without adjusting the timetable by assuming that all trains run with a length of one RS unit, the Base Model may thus have a very limited time horizon. The time horizon for the RS-SSP-MU, in contrast, can start with the first train arriving at a turning station and end with the last departing train before the evening peak.

In order to allow trains to run with multiple RS units, two constraints of the Base Model need to be adapted. The extended model can then be formulated as:

$$maximise \sum_{u \in RS} \sum_{i \in I} z'_{u,i} \tag{21}$$

subject to (2)-(10); (12)-(19)

$$\sum_{u \in RS} x_{u,k} = RS_k^{nr} \; \forall k \in K^{arr} \tag{22}$$

$$\sum_{u \in RS} (y_{u,i} - y'_{u,i}) = (RS^{nr}_{arr(i)} - RS^{nr}_{dep(i)}) \; \forall i \in I \setminus \{0\} \tag{23}$$

As can be seen in the model formulation above, Constraint (11) is replaced by Constraint (22). Instead of limiting the number of RS units per train to one, the new parameter RS_k^{nr} specifies the number of RS units running in train k.

Furthermore, Equation (20) is replaced by Equation (23). Equation (23) ensures that the number of RS units entering the SL minus the number of RS units leaving the SL in phase i is equal to the difference in number of RS units running in the arrival and the departing train in phase i.

4.4. RS-SSP with Multiple Units and Waiting for Servicing

In this section the RS-SSP-MU is extended by the possibility that RS units wait at the SL for being serviced. Hence, the servicing duration might start at a later stage as compared to the moment that the RS unit enters the SL. The second extended model is called RS-SSP-MU-W, whereby the 'W' stands for waiting for servicing.

Both the RS-SSP Base Model and the RS-SSP-MU assume that an RS unit entering the SL will directly be serviced. However, in reality this might not be the case. Insufficient cleaning platforms, personnel, or equipment may be reasons for a limited number of RS units being in service simultaneously. In the RS-SSP Base Model and the RS-SSP-MU RS units would not be allowed to enter the SL in case the maximum number of RS units is being serviced at that moment. Sometimes this restriction may lead to a dismissed possibility of cleaning an RS unit. By allowing RS units to wait for being serviced, additional RS units might be serviced during daytime.

For the RS-SSP-MU-W, a new binary decision variable needs to be introduced. $z_{u,i}$ indicates whether an RS unit u starts being serviced at the start of phase i.

Figure 3 visualises the extension of the RS-SSP. Instead of two nodes representing the SL as in Figure 2, the SL consists of 3 nodes. After arriving at the turning station (arr) at phase i, an RS unit u has still two options: departing in train $dep(i)$ (i.e. $y_{u,i} = 0$) or entering the SL (i.e. $y_{u,i} = 1$). When entering the SL, however, the RS unit might need to wait until it is serviced. Therefore, an additional node is created. Phase $i + p$ is the phase in which the RS unit u starts being serviced (i.e. $z_{u,i+p} = 1$). Note that p indicates the number of phases in which the RS unit u needs to wait at the SL until it starts being serviced. Obviously, it is possible that p is 0, meaning that the RS unit u can directly be serviced when entering the SL. From the moment that the RS unit u starts being serviced at the assembly node u_{i+p}, the procedures equal that described in Figure 2.

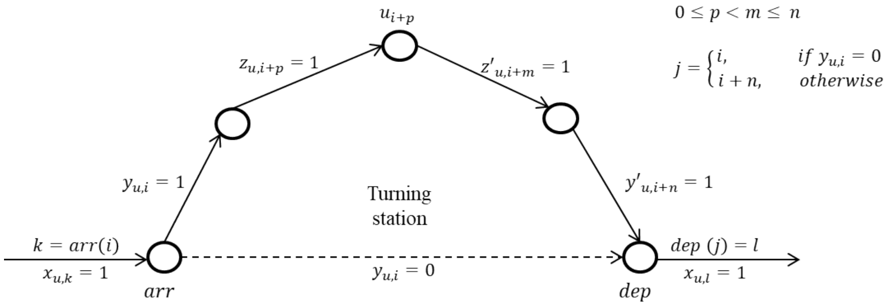

Figure 3: Decisions at the turning station when allowing RS units to wait for servicing.

The RS-SSP-MU-W[2] is formulated as follows.

$$maximise \sum_{u \in RS} \sum_{i \in I} z'_{ui} \tag{24}$$

subject to (2)-(5); (7)-(10); (12)-(13); (16)-(19); (22)-(23)

$$z_{u0} = 0 \ \forall u \in RS \tag{25}$$

$$u_{i+1} = u_i + \sum_{u \in RS} z_{ui} - \sum_{u \in RS} z'_{ui} \ \forall i \in I \tag{26}$$

$$z'_{ui} \cdot d^{max} \le (\tau^{arr}_{arr(i)} - \sum_{j=0}^{i} (z_{uj} \cdot \tau^{arr}_{arr(j)})) \ \forall u \in RS \setminus RS^{SL_0} \tag{27}$$

$$z'_{ui} \le \sum_{j=0}^{i} z_{uj} \ \forall u \in RS, i \in I \tag{28}$$

$$z_{ui} \le \sum_{j=0}^{i+1} y_{uj} \ \forall u \in RS, i \in I \tag{29}$$

$$\sum_{i \in I} z_{ui} \le 1 \ \forall u \in RS \tag{30}$$

Equation (25) fixes the initial value of the new variable $z_{u,0}$ by setting it

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[2] Note that the first extension allowing trains to run with multiple RS units is also included in the RS-SSP-MU-W.

to zero. Furthermore, Equation (26) replaces Equation (6). While Equation (6) increases the number of the assembly u_{i+1} when the sum of $y_{u,i}$ over all RS units u is positive, Equation (26) counts the sum of $z_{u,i}$. Regarding the difference between Figure 2 and Figure 3, the replacement of Equation (6) by Equation (26) becomes clear. Due to the possibility that RS units wait for being serviced after entering the SL, the decision whether an RS unit will be serviced is not taken by y anymore, but by z.

Constraint (14) is replaced by Constraint (27) as it is required to track the moment in time an RS unit starts being serviced rather than the moment in time it entered the SL in order to know whether the RS unit completed servicing.

Also, the Equation (15) is replaced by Constraint (28) ensuring that an RS unit cannot complete service before having started being serviced.

Constraints (29) and (30) are additions to the RS-SSP defining the limits of the new variable $z_{u,i}$. Similar to the Equation (28), Constraint (29) ensures that an RS unit can only start being serviced if it entered the SL before. Note that the option of servicing an RS unit immediately when entering the SL is still available. Finally, Constraint (30) ensures that each RS unit will only be serviced once.

5. Computational Experiments

The model was applied to real-life instances in the Netherlands. In particular, we consider the Sprinter train series (i.e. Dutch local trains) commuting between Zwolle and Utrecht (i.e. train series 5600). This train series was chosen because of its high consistency in the RS circulation. As opposed to other train series, the RS units used in the train series 5600 normally stay within this train series. Therefore, the RS units can easier be traced. Note that RS units leaving the train series cannot be traced when focusing on one single train series. Multiple scenarios regarding this train series were created and applied to the RS-SSP Base Model, the RS-SSP-MU, and the RS-SSP-MU-W. Section 5.1 defines the case study, Section 5.2 focuses on the validation of the RS-SSP by experimenting with the RS-SSP Base Model, and Section 5.3 entails a comparison of the three models. After developing the mathematical model, the RS-SSP model was coded in Python using Gurobi as solver.

5.1. Case study

Multiple scenarios were created with respect to the selected Sprinter train series 5600 considering Zwolle as available service location for daytime servicing. The scenarios feature one or multiple changes of the Base Scenario, which is based on the planned RS circulation (NS, 2019). The main characteristics of the Base Scenario are listed in Table 4.

τ_k^{arr}	{11:06, 11:36, ..., 17:06}	[hh:min]
T_u^{in}	{09:06, 09:36, ..., 11:06}	[hh:min]
RS	{1, 2, 3, 5, 8, 10, 11, 12, 13, 14, 15} [3]	
RS^{SL_0}	{1, 3, 11, 14, 15}	
SL_0	5	
tt_k	00:17	[hh:min]
tt^{min}	00:10	[hh:min]
d^{max}	02:00	[hh:min]
SL^{max}	5	

Table 4: Parameter values for the Base Scenario

5.2. Experimenting with the RS-SSP Base Model

A large number of scenarios were applied to the RS-SSP Base Model as described in Van Hövell (2019). It should be mentioned that the RS-SSP Base Model considers single-unit trains and a time horizon starting with the train arriving at 11:06 and ending with the last train departing before the start of the evening peak at 17:23. The reason for this selected time horizon is based on the RS units being available for an RS exchange. The timetable applied to the RS-SSP Base Model is visualised in Figure 4.

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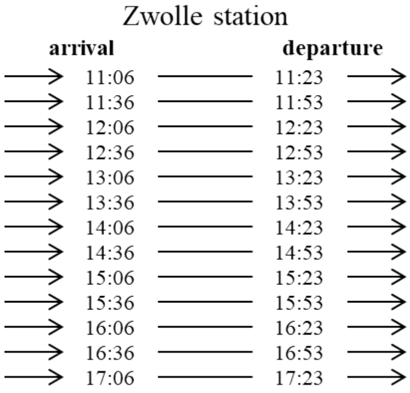
[3] Note that the irregular numeration of RS units is based on the planned RS circulation.



Zwolle station

arrival	departure
11:06	11:23
11:36	11:53
12:06	12:23
12:36	12:53
13:06	13:23
13:36	13:53
14:06	14:23
14:36	14:53
15:06	15:23
15:36	15:53
16:06	16:23
16:36	16:53
17:06	17:23

Figure 4: Timetable as applied to the RS-SSP Base Model

Table 5 provides the outcomes for the RS-SSP Base Model regarding single parameter changes. In the first column six input parameters are listed as they are examined with respect to changing values. The second column entails the diverse values used for the changing parameter. The third column gives the resulting values of the objective function (OF) for the Base Scenario, with the value of the changing parameter being adapted accordingly. The fourth column (#RS) indicates the total number of RS units being used for the corresponding scenario. Then, the sixth column (OF/#RS) shows the percentage of RS numbers being serviced in relation to the total number of used RS units, called servicing rate. Finally, the last column provides additional comments, where necessary.

As can be seen in Table 5, the outcome of the objective function increases for increasing numbers of RS units initially standing at the SL (i.e. SL_0). The servicing rate, however, reaches 100% already with $SL_0 = 3$ and does not improve for higher values of SL_0. For SL_0 smaller or equal to 2, it is not possible to let all RS units complete servicing. Note that for values of SL_0 larger than 5, SL^{max} is set equally to SL_0 (see comment). The turning time of train k (i.e. tt_k) and the minimum required turning time tt^{min} are directly related to each other. For $tt^{min} \leq tt_k$, the objective function achieves the maximum possible value (i.e. 11). $tt^{min} \geq tt_k$, however, implies that RS units cannot be exchanged. Therefore, only the RS units standing initially at the SL can be serviced. The maximum allowed number of RS units being serviced simultaneously (i.e. SL^{max}) is related with SL_0. In case $SL^{max} \geq SL_0$, the parameter does not present any limitations. For $SL^{max} \leq SL_0$, however, the solutions become infeasible. This is due to the assumption that RS units get serviced immediately when entering the SL. In most of the remaining cases all RS units have been exchanged (i.e. 100% servicing rate). However, a servicing duration (d^{max}) of 3 hours as well as a train arrival frequency of every 15 minutes do not allow all used RS units to be serviced.

Changing Parameter	**Parameter Value**	**OF**	**#RS**	**OF/#RS**	**Comment**
SL_0	1	4	7	57%	
	2	7	8	88%	
	3	9	9	100%	
	4	10	10	100%	
	5	11	11	100%	
	6	12	12	100%	$SL^{max} = 6$
	14	20	20	100%	$SL^{max} = 14$
tt_k	$\geq tt^{min}$	11	11	100%	
	$< tt^{min}$	5	11	45%	no RS exchange
tt^{min}	$\leq tt_k$	11	11	100%	
	$> tt_k$	5	11	45%	no RS exchange
SL^{max}	$\geq SL_0$	11	11	100%	
	$< SL_0$	infeasible	11	-	infeasible
d^{max}	00:30	11	11	100%	
	01:00	11	11	100%	
	02:00	11	11	100%	
	03:00	10	11	91%	
headway	15	15	17	88%	
	30	11	11	100%	
	60	8	8	100%	

Table 5: Single parameter changes

The impact of SL_0 is further analysed in Figure 5. Here, the outcomes with a 15-minutes headway are contrasted with the 30-minutes headway. It can be seen that for the higher train arrival frequency, larger values are required for SL_0 in order to obtain a 100% servicing rate.

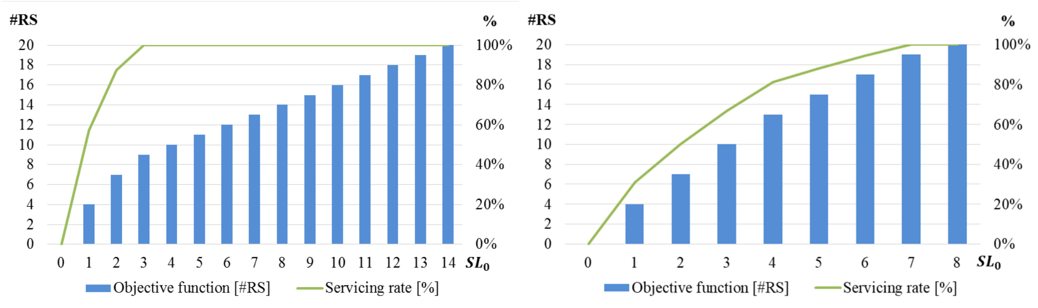


Figure 5: Impact of SL_0 with a 30-minutes headway (left) and a 15-minutes headway (right)

5.3. Model Comparison

One crucial advantage of the RS-SSP extensions (i.e. RS-SSP-MU and RS-SSP-MU-W) is the possibility of extending the time horizon. Instead of starting at 11:06, when the first RS unit can be exchanged according to the planned RS circulation, the RS-SSP extensions can be applied to a time horizon starting at 7:06, when the first train arrives at Zwolle station. The reason for this is that the RS-SSP-MU models can handle trains running with multiple RS units and also allow RS units to enter the SL without enforcing an RS exchange. Remember that the RS-SSP Base Model only allows RS exchanges for trains with single RS units and thus RS units would need to be initially at the SL in order to enable operating RS units to enter the SL.

The timetable as provided by the planned RS circulation is visualised in Figure 6, whereby double arrows stand for trains running with two RS units and single arrows for single-RS-unit-trains. The different time horizons considered by the model extensions (i.e. RS-SSP-MU and RS-SSP-W) and the RS-SSP Base Model are indicated on the right side of the figure.

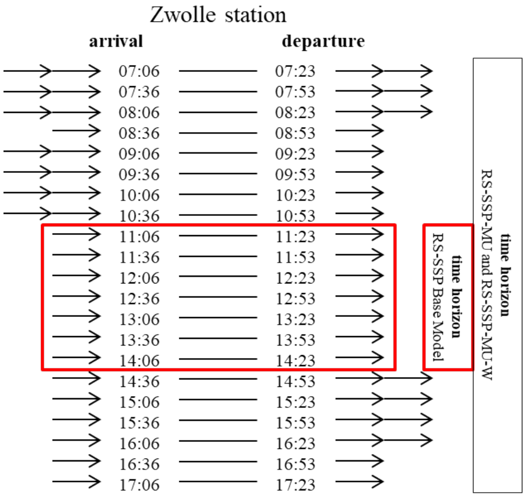


Figure 6: Timetable according to the planned RS circulation (NS, 2019)

Table 6 presents a comparison of the three models based on single parameter changes. By experimenting with the three RS-SSP model versions large differences between the RS-SSP Base Model and the two extended versions could be determined. Mainly, the short time horizon is a huge disadvantage of the Base Model as it leads to significantly lower OF values as opposed to the results of the two extended models. The outcomes of the RS-SSP-MU and the RS-SSP-MU-W are very similar yet the RS-SSP-MU-W provides more feasible solutions with respect to low values for SL^{max}. This is due to the functionality of the RS-SSP-MU-W allowing RS units to wait for being serviced. The two extensions made on the RS-SSP Base Model were, thus, proven to be of high value.

Changing Parameter	**Parameter Value**	**Objective Function**		
		RS-SSP	**RS-SSP-MU**	**RS-SSP-MU-W**
SL^{max}	1	infeasible	infeasible	infeasible
	2	infeasible	infeasible	7
	3	infeasible	infeasible	10
	4	infeasible	infeasible	11
	5	8	11	11
d^{max}	00:30	11	11	11
	01:00	10	11	11
	02:00	8	11	11
	03:00	5	9	9

Table 6: Single Parameter Changes

Figure 7 visualises the decreasing values of the objective function for increasing values of d^{max}. The blue bars present the course of the RS-SSP Base Model and the red bars show the course of the two extended models (i.e. RS-SSP-MU and RS-SSP-MU-W). The left figure assumes a 30-minutes headway, whereas the right figure considers a 15-minutes headway. It becomes clear that the extended models reach the maximum value (i.e. servicing rate of 100%) already with a servicing duration of two hours, whereas the Base Model only achieves a 100%-servicing rate with a servicing duration of 30 minutes and a headway of 30 minutes.

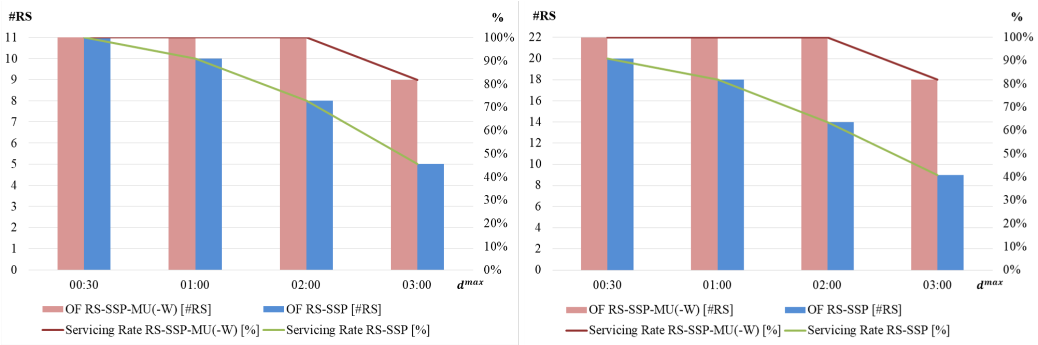


Figure 7: Impact of d^{max} with a 30-minutes headway (left) and a 15-minutes headway (right)

In Figure 8, the three models are contrasted with respect to different values for SL^{max} assuming a servicing duration of three hours. It shows that none of the models obtains solutions where all RS units complete servicing. For values of SL^{max} higher or equal to 5, the models obtain the best possible solutions. The two more extended model versions achieve an 80%-servicing rate and the RS-SSP Base Model a 45%-servicing rate. For values of SL^{max} lower than 5, however, only the RS-SSP-MU-W gains feasible solutions.

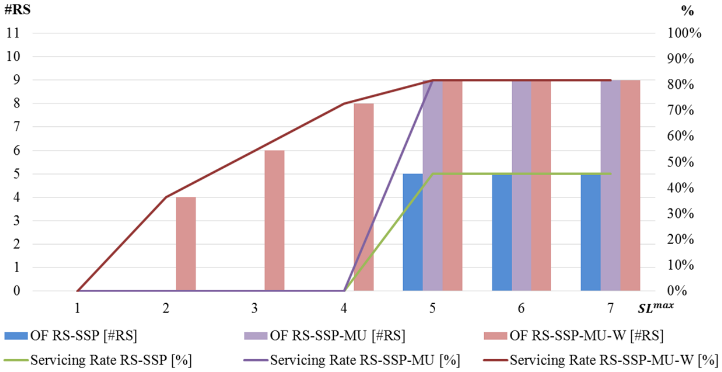


Figure 8: Impact of SL^{max} with d^{max} of 3 hours

It can be concluded that changing several input parameters have positive influence on the maximum number of RS units being serviced during daytime. Obviously, lower train frequencies, higher service capacities, shorter servicing durations, larger turning times, faster RS exchanges, and additional RS units standing at the SL never downgrade the outcome, yet they do not automatically enhance results. As shown for the case of the Sprinter train series 5600 between Zwolle and Utrecht, there are critical values which need to be respected (e.g. regarding tt_k, tt^{min}, SL_0, and SL^{max}). When extending the RS-SSP on other train series, these critical values would need to be specified. Accordingly, supportive adaptations on the timetable or servicing efficiency can be discovered.

6. Discussion

With respect to the applicability of the RS-SSP, multiple strengths could be identified. The capacity at SLs, for instance, can be increased by means of implementing the RS-SSP. Furthermore, the work pressure of night workers might be decreased by balancing the workload over the entire day. This may lead to a higher employee satisfaction. Moreover, the work efficiency of technicians during daytime will be improved by increasing the number of RS units visiting the SL during daytime. In addition, the servicing performance rate can be improved as the possibility of daytime servicing provides additional buffer time. This may also increase the passenger satisfaction because of cleaner trains.

Despite of the advantages, several challenges need to be overcome when implementing the RS-SSP. Firstly, the need of passengers for clean trains in the morning needs to be addressed when switching from servicing at night towards daytime. Secondly, the RS Exchange Concept implies additional train drivers as long as automated trains are not used. Thirdly, sufficient servicing personnel needs to be available during daytime, which might require additional employments. Furthermore, the limited accessibility of certain SLs – due to regular train operations – may cause difficulties for daytime servicing. In addition, operational disruptions can cause deviations from the plan. This may lead to reallocations or even cancellations of servicing appointments during daytime. In addition, the differences in prioritisation of RS controllers and SL managers complicate the cooperation between the two parties, which is considered as a prerequisite for implementing the RS-SSP.

7. Conclusions

In this paper the Rolling Stock Servicing Scheduling Problem (RS-SSP) model has been introduced to solve the lack in RS servicing capacity. The RS-SSP increases the efficiency of the RS servicing capacity by allowing daytime servicing and introducing RS exchanges between serviced and operating RS units requiring servicing. We developed three model variants. While the first model represents the Base Model of the RS-SSP, the second model (i.e. RS-SSP-MU) is an extended version allowing trains to run with multiple RS units. The third model (i.e. RS-SSP-MU-W) is a further extension allowing RS units to wait at the SL for being serviced. Computational experiments were performed on the Dutch railway network. Results showed that the most extended model version achieved the most feasible and optimal solutions. Due to its network perspective, the RS-SSP is a very generic model, which cannot only be applied to multiple railway companies but also to other public transport systems such as metro, tram, and bus networks. As metro and tram networks also involve track infrastructure, they face large similarities to railway networks facilitating the applicability of the RS-SSP. Due to less differences in RS types, the current RS-SSP version might even be more suitable to metro or tram operations than to railways. Aside of overland transportation, the RS-SSP may also be interesting for the fleet management in air or water traffic. However, airlines may have additional requirements with respect to competing airlines being serviced at the same node (i.e. airport). Regarding water traffic, ferries with regular line service might be considered. To what extent the RS-SSP is applicable to airlines or ferries would need to be further investigated.

Further research is suggested in order to extend model functionality and analyse the feasibility of the RS-SSP. In order to generate optimal solutions on a large scale, the RS-SSP model should be extended by considering multiple SLs and multiple RS types. Furthermore, the diverse service locations need to be analysed in order to wisely select suitable SLs being available for daytime servicing. In addition, the passenger and employee satisfaction should be investigated. Note that both the passengers' and the employees' points of view are very important when thinking about a system change such as caused by the RS-SSP.

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