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van Hövell, Madeleine E.M.A. ; Goverde, Rob M.P.; Bešinović, Nikola; de Weerdt, Mathijs M.

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Increasing the effectiveness of the capacity usage at rolling stock service locations

Madeleine E.M.A. van Hövell [a,*], Rob M.P. Goverde [a], Nikola Bešinović [a], Mathijs M. de Weerdt [b]

[a] *Delft University of Technology, Department of Transport and Planning, Stevinweg 1, 2628 CN Delft, The Netherlands*
[b] *Delft University of Technology, Department of Software and Computer Technology, Van Mourik Broekmanweg 6, 2628 XE Delft, The Netherlands*

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ABSTRACT

Trains consist of one or more railway vehicles called rolling stock, which need interior and exterior cleaning and small technical checks on a daily basis. These services are executed at service locations (SLs). Scheduling rolling stock servicing tasks during an operational day is important to guarantee the fulfilment of servicing deadlines. Public transport companies face large scheduling problems, especially those with 24-hour-a-day operation. The expected increase in transport frequencies enhances the need for improving scheduling servicing tasks during an operational day. Therefore, the Rolling Stock Servicing Scheduling Problem (RS-SSP) is modelled comprising a MILP model. 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. The proposed RS-SSP model has been tested on a real-life case from the Dutch railways. For multiple scenarios, the model was able to exchange all running RS. Consequently, the capacity usage at SLs can be increased by the RS-SSP by shifting some of the excessive workload to daytime, and thus solving the capacity shortages.

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. According to Mo and Sinha (2014), servicing tasks are performed when RS units are not required for operations. In the railway industry RS units are mostly serviced during the evening and night because of operations during daytime. Operational disruptions often lead to skipped cleaning tasks due to a lack in servicing capacity based on the short servicing time period. Servicing capacity is defined as the number of rail carriages that can be serviced per day at a service location. Multiple metro operators, however, committed to a 24-hour-a-day operation (e.g. in New York, Melbourne, and Copenhagen) facing even more difficulties with respect to scheduling servicing tasks (Zicla, 2017). In either case, the challenge is to find time windows for servicing tasks in order to ensure that RS units meet their servicing deadlines. Depending on the servicing task, the servicing frequency may vary between once every 24 h (for interior cleaning), multiple times per week (for technical checks), and once per week (for exterior cleaning).

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

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In order to find a solution for more effectively using the capacity at service locations, the focus is on scheduling servicing tasks during an operational day. At the Dutch railway operator Nederlandse Spoorwegen (NS), for instance, several RS units move 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 challenge is that the currently waiting RS units need to be serviced within about five hours in order to be ready for the peak hour operations. In order to ensure the timely provision of the RS units, multiple cleaning personnel would need to work parallel. However, the working time of these cleaning personnel cannot be spread over the entire work shift leading to unusable remaining working hours of the cleaning personnel. 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 has completed servicing, it may substitute an operating RS unit arriving at a terminal station nearby the SL. By exchanging serviced RS units with RS units requiring servicing, the number of RS units visiting the SL during daytime increases. This leads to more work for servicing personnel making daytime servicing more efficient. Efficient daytime servicing refers to a minimum number of rolling stock units, which needs to be available at a service location to ensure that servicing personnel has sufficient work. Besides, more RS units can complete servicing during daytime. RS units that 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 – where not all RS units can be serviced with respect to their servicing deadlines – 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 this paper, we introduce the Rolling Stock Servicing Scheduling Problem (RS-SSP) to model the Rolling Stock Exchange Concept. 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 as well as the adjustments of the RS circulation, i.e. which pairs of RS units are exchanged. This paper is based on a thesis that has been published in an institutional repository (Van Hövell, 2019).

The main contributions of this paper are:

1. A new RS exchange concept, providing possibilities of exchanging rolling stock during daytime
2. A new mathematical model RS-SSP optimising the effectiveness of the capacity usage at service locations
3. Experimental testing of the RS-SSP model on real-life instances of the Dutch railways showing an increase in servicing capacity

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. Computational experiments are described in Section 5 and 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 and checked, and repaired when 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 with large fluctuations in workload distribution, which are prone to violate timelines (Lai et al., 2015). In the past, models have been established with respect to maintenance planning. An example from the aerospace context is Feo and Bard (1989), who tried 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), Zhong et al. (2019), and Wu and Lai (2019) developed an optimisation model for scheduling large RS maintenance tasks, which incorporated several maintenance planning constraints. Penicka et al. (2003) presented a model solving the RS maintenance routing problem. The maintenance routing problem is concerned with finding a routing of the RS which satisfies the deadlines of maintenance tasks. However, maintenance constraints were not 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. Their algorithm aims to find the minimal cost flow in the constructed network. Also, Borndörfer et al. (2011) proposed a model for the RS circulation planning in consideration of the cleaning and maintenance time. Moreover, Tönissen and Arts (2018) solved a maintenance location routing problem minimising the total annual facility costs. The model allows exchanges between RS units, yet only large maintenance works such as overall technical checks, battery changes or reparation of air condition 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

Table 1
Literature overview regarding RS planning.

	RS related			Maintenance related				
	RS allocation	RS circulation	RS exchanges	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			
Zhong et al. (2019)	x			x	x			
Wu and Lai (2019)	x			x	x			
Penicka et al. (2003)		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		
Lai et al. (2015)		x	x	x			x	
Andrés et al. (2015)		x	x	x			x	
Zomer et al. (2020)		x					x	x
Zomer et al. (2021)		x					x	x
This paper		x	x				x	x

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 for rapid transit networks using an efficient Bellman–Ford's multilevel algorithm for each train type. Both last models have taken multiple regulations into account such as train scheduling and maintenance constraints and focus on daily and monthly inspections.

Zomer et al. (2020) introduced the Maintenance Location Choice Problem (MLCP). For a given and fixed rolling stock circulation, the proposed model provided an optimal maintenance location choice minimising the total number of maintenance activities during nighttime. Zomer et al. (2021) also included the capacity of maintenance locations and determined exact maintenance schedules considering actual moments when maintenance has to be performed.

In Table 1 an overview of studies regarding RS planning is given, distinguishing the incorporated aspects (see columns). Those aspects are either related to the routing of rolling stock, or to the type of maintenance tasks. The first aspect "RS allocation" refers to the allocation of maintenance tasks to RS units, whereby "RS circulation" involves the entire routing of RS units. Not all the listed papers considering the RS circulation also take "RS exchanges" into account. Regarding the maintenance related aspects, papers are classified by the considered types of maintenance. It can be seen that large maintenance works have been mostly addressed, whereby daytime cleaning has been neglected. Also, the RS-SSP model is included in this overview.

Several research gaps can be identified in the current literature. First, most of the existing models do not consider the efficient usage of maintenance facilities with respect to an equal workload distribution (inter alia Penicka et al., 2003, Maróti and Kroon, 2007, Borndörfer et al., 2011). Second, only several papers allow changes in the RS circulation plan in order to route urgent RS units to a maintenance facility (see Table 1 "RS exchanges"). Regarding Maróti and Kroon (2005, 2007), for instance, it is possible to exchange tasks of urgent RS units with non-urgent RS units. Third, the existing models, except Zomer et al. (2020, 2021), do not take interior cleaning of RS into account, which needs to be executed every 24 h. The high frequency of interior cleaning tasks calls for a model allowing all RS units being routed to a maintenance facility everyday. Although Zomer et al. (2020, 2021) considered daytime servicing, these did not include RS exchanges but only fixed RS circulations. RS exchanges as proposed in this paper have not been considered in any study before according to the best of the author's knowledge. As opposed to the RS exchange from Maróti and Kroon (2007), this paper considers RS exchanges between RS units of running trains and RS units standing at a service location. This allows a very large number of RS exchanges. The model developed in this paper is the first that combines daily daytime servicing (with a 24 h meantime between cleaning) and the new concept of RS exchanges. The daily frequency influences the model as all RS units feature approximately the same deadline. The importance of more or less urgent RS units is thus decreased, compared to e.g. Maróti and Kroon (2005).

Hence, a new mathematical model is developed for the Rolling Stock Servicing Scheduling Problem determining which rolling stock units should be exchanged at which time in order to improve the capacity usage at SLs.

3. Problem description

In order to describe the RS-SSP, Fig. 1 visualises a conceptual model. The input of the model consists of the planned RS circulation, the RS exchange parameters, and SL related information (see Fig. 1). Those input parameters are all based on planned data and

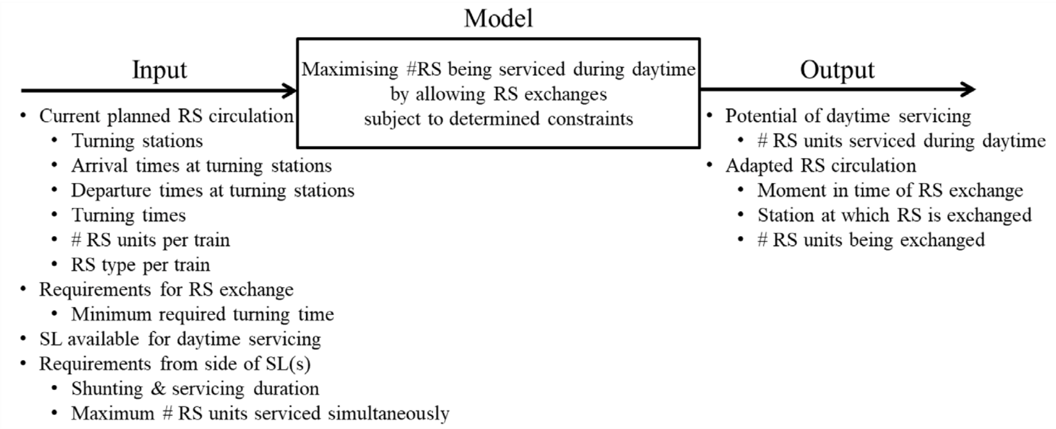

Fig. 1. Conceptual model.

estimations given by the operator (e.g. NS). The planned RS circulation entails the routing of a single RS unit including the terminal 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 default values. Note that the increase in turning time due to additional de-/coupling is not taken into account. 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. Note that those two requirements may vary between SLs. The model developed in this paper assumes a single SL to be available for daytime servicing. The underlying servicing tasks refer to daily services such as smaller inspections and interior cleaning. Furthermore, a single rolling stock type and no additional costs for daytime servicing at a SL are considered in this research.

The box in Fig. 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 features. 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 during which time.

The RS-SSP is further explained by the following example. Table 2 visualises the timetable of a train line arriving at and departing from one terminal station. In total 11 RS units are used for operations as indicated by the different colours in Table 2. Each colour indicates an RS unit to follow its circulation and when it enters the service location. In case a train consists of a single RS unit, the arrival or departure time of that train is highlighted with a single colour. In case of a train with two rolling stock units, the arrival or departure time is highlighted by two colours. For instance, the train arriving at 08:36 consists of the single red marked rolling stock unit, whereas the train arriving at 09:06 consists of two – the dark blue and the light blue – RS units. The cycle time, which is the duration from the moment that a train departs from the terminal station until it returns to the same station, is 2 h and 43 min. All trains visible in the timetable of Table 2 feature the same cycle time. The first train arrives at 8:36 and the last train at 17:06. From 9:06 to 11:06 trains arrive with a length of 2 RS units and are decoupled at the terminal 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).

As can be seen in Table 2, it is assumed that no RS unit is on reserve at the SL before 08:36. Due to a shunting and servicing duration of two hours 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 Table 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 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.

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

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

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. One of the most used indices is phase i, which is defined as the time period between train arrival i and train arrival $i+1$. 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.

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 Fig. 2 the decisions to be taken at the terminal station are visualised, including the resulting RS movements. All variables are located at an arc or node within the figure. The figure shows a terminal station consisting of four different nodes. The arrival (arr) at and the departure (dep) from the terminal 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 that 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 the RS unit u are 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

Table 3
Model components.

Sets		
I	set of train arrivals	
K^{arr}	set of arriving trains	
K^{arr_0}	set of first arriving trains without 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	$u_i \in \mathbb{Z}_0^+$

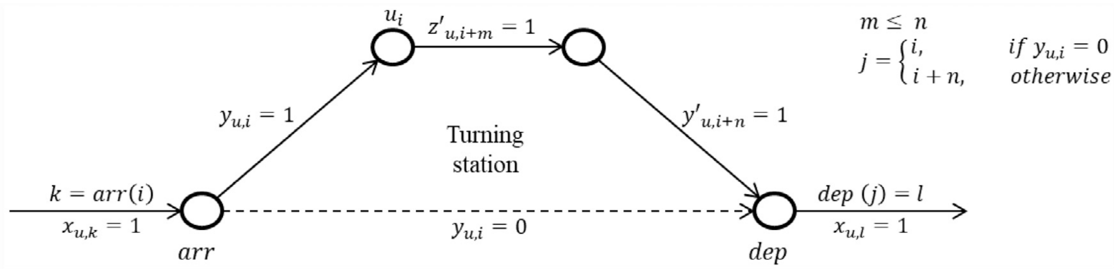

Fig. 2. Decisions at the terminal station.

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.

4.2. RS-SSP base model

The RS-SSP Base Model is formulated by the following objective function and constraints.

Objective function

The objective function maximises the total number of rolling stock units which completed servicing during daytime:

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

Initialising constraints

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

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

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

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

Constraints (2) and (3) set the initial decision variable $y_{u,0}$ to 1 or 0 depending on whether RS unit u stands initially at the SL or not. Furthermore, Eq. (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.

Servicing demand and capacity constraints

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

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

Eq. (6) tracks the number of RS units being in service in phase $i+1$. 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}).

RS circulation constraints

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

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

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

An RS unit can only enter the SL in phase i if that RS unit runs in the train arriving in phase i (see Constraint (8)). Eq. (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, as formulated in Eq. (10), 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 $\sigma(l)$.

Timetable constraints

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

Eq. (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.

Turning time and servicing duration constraints

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

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

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

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}).

SL entering and leaving constraints

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

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

$$\sum_{u\in RS} y_{u,i} = \sum_{u\in RS} y'_{u,i}, \quad \forall i \in I \setminus \{0\}. \tag{17}$$

Constraint (15) ensures that an RS unit can only be serviced in case it entered the SL. Constraint (16) guarantees that the RS unit only leaves the SL in case it has been fully serviced. Constraint (17) ensures that an RS unit can only enter the SL if another RS unit leaves the SL in the same phase.

Double work constraints

$$\sum_{i\in I} y_{u,i} \leq 1, \quad \forall u \in RS \tag{18}$$

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

$$\sum_{i\in I} z'_{u,i} \leq 1, \quad \forall u \in RS. \tag{20}$$

Furthermore, RS units must not visit or leave the SL multiple times per day. Hence, Constraint (18) avoids that an RS unit u visits the SL more than once during the same day and Constraint (19) ensures that each RS unit leaves the SL at most once. In addition, Constraint (20) guarantees that no double servicing is done.

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 assumes that all trains run with a length of one RS unit. In reality, this assumption is typically applicable to most metro or tram systems, however, in the conventional railway context trains often run with multiple RS units especially in the peak hours. By means of allowing trains to run with a length of multiple RS units, the time horizon for railway applications can be extended starting with the first train arriving at a terminal station and ending 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. 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 RS-SSP-MU can then be formulated as:

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

subject to (2)–(10), (12)–(16), (18)–(20), and

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

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

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, Eq. (17) is replaced by Eq. (23). Eq. (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 with 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. This may be the case for service locations with high work capacity and/or low parking space. However, 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. Fig. 3 visualises the extension of the RS-SSP. Instead of two nodes representing the SL as in Fig. 2, the SL consists of 3 nodes. After arriving at the terminal 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,

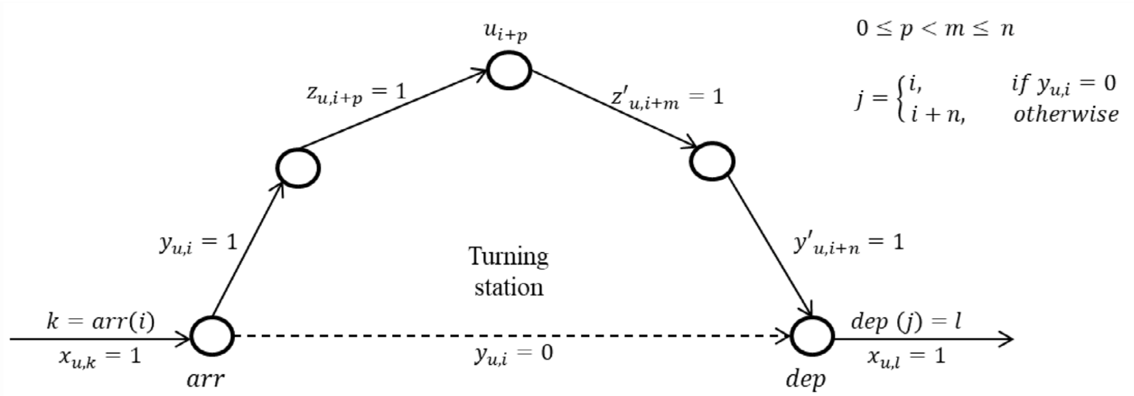

Fig. 3. Decisions at the terminal station when allowing RS units to wait for servicing.

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 Fig. 2.

The RS-SSP-MU-W is formulated as follows. Note that the first extension allowing trains to run with multiple RS units is also included in the RS-SSP-MU-W.

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

subject to (2)–(5), (7)–(10), (12)–(13), (16), (18)–(20), (22)–(23), and

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

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

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

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

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

$$\sum_{i \in I} z_{ui} \leq 1, \quad \forall u \in RS. \tag{30}$$

Eq. (25) fixes the initial value of the new variable $z_{u,0}$ by setting it to zero. Furthermore, Eq. (26) replaces Eq. (6). While Eq. (6) increases the number of the assembly u_{i+1} when the sum of $y_{u,i}$ over all RS units u is positive, Eq. (26) counts the sum of $z_{u,i}$. Regarding the difference between Figs. 2 and 3, the replacement of Eq. (6) by Eq. (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, Eq. (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 Eq. (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 line (i.e. Dutch local trains) commuting between Zwolle and Utrecht (i.e. train line 5600). This train line was chosen because of its high consistency in the RS circulation. As opposed to other train lines, the RS units used in the train line 5600 normally stay within this train line. Therefore, the RS units can easier be traced. Note that RS units leaving the train line cannot be traced when focusing on one single train line. Multiple scenarios regarding this train line were created and applied to the RS-SSP Base Model, the RS-SSP-MU, and the RS-SSP-MU-W. While Section 5.1 defines the case study, Section 5.2 focuses on the validation of the RS-SSP by experimenting with

Table 4
Parameter values for the Base Scenario.

Parameter	Value(s)	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
Problem size regarding the Base Scenario.

	RS-SSP	RS-SSP-MU	RS-SSP-MU-W
Parameters	93	106	106
Binary Variables	605	605	759
Integer Variables	14	14	14

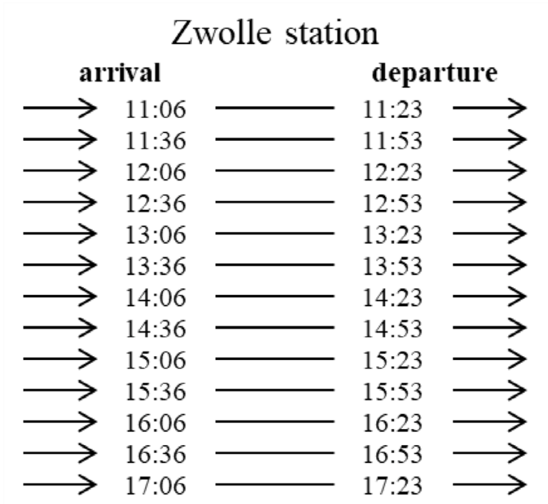

Fig. 4. Timetable as applied to the RS-SSP Base Model.

the RS-SSP Base Model. In Section 5.3 the three models are compared with each other in order to prove the benefit of the two model extensions. In addition, the impact of individual parameter changes is identified by means of computational experiments. 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 line 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. Note that the irregular numeration of RS units is based on the planned RS circulation (see parameter RS). Furthermore, in Table 5 the number of parameters and variables are indicated for each model with respect to 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 Fig. 4.

Table 6 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 varying values. The second column entails the values used for the

Table 6
Single parameter variations.

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

corresponding parameter. The third column gives the resulting values of the objective function (OF) for the Base Scenario, with the value of the 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. The seventh column provides additional comments, where necessary. Finally, the last column entails the computation time (CPU) for each scenario.

As can be seen in Table 6, 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). $tt^{min} > tt_k$, 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 $SL^{max} < SL_0$, however, the model becomes infeasible. An infeasible model means that there is no solution that satisfies all constraints. 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 h as well as a train arrival frequency of every 15 min do not allow all used RS units to be serviced within the assumed time horizon. It can be seen that lower frequencies lead to more efficient use of the SL capacity, while it drops when the frequency increases. This result demonstrates a greater challenge in case of high train frequencies as not all rolling stock may be exchanged for being serviced during daytime. All experiments with the RS-SSP Base Model have a computation time of less than one second.

The impact of SL_0 is visualised in Fig. 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.

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 Fig. 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.

Table 7 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

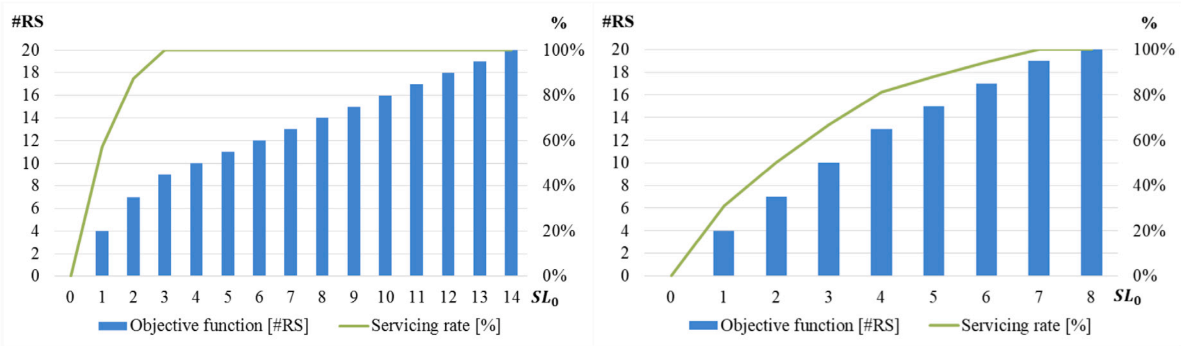

Fig. 5. Impact of SL_0 with a 30-minutes headway (left) and a 15-minutes headway (right).

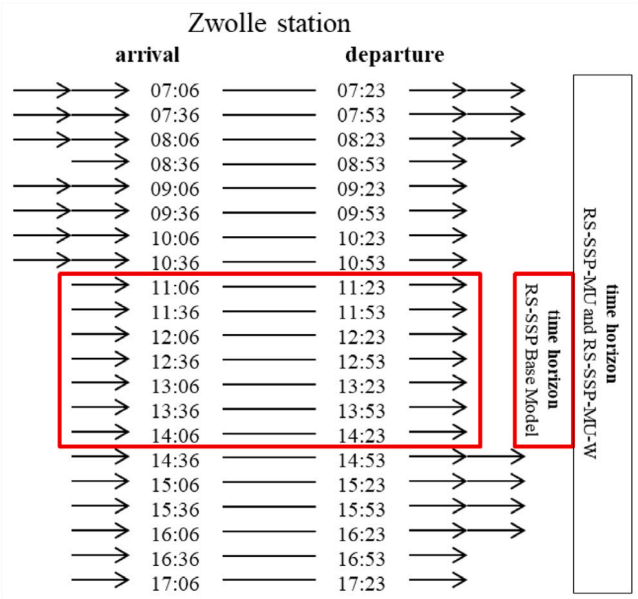

Fig. 6. Timetable according to the planned RS circulation (NS, 2019).

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. Regarding the computation times, both the RS-SSP Base Model and the RS-SSP-MU model feature constantly values of less than one second. The RS-SSP-MU-W model shows slightly higher computation times. Tighter restrictions seem to increase the effort of finding an optimal solution as can be seen from the first two scenarios with a CPU of 25 and 73 s.

Fig. 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 min and a headway of 30 min.

In Fig. 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.

It can be concluded that changing several input parameters has 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

Table 7
Single parameter variations.

Parameter	Parameter Value	RS-SSP OF	RS-SSP CPU	RS-SSP-MU OF	RS-SSP-MU CPU	RS-SSP-MU-W OF	RS-SSP-MU-W CPU
SL^{max}	1	infeasible	< 1 s	infeasible	< 1 s	infeasible	25 s
	2	infeasible	< 1 s	infeasible	< 1 s	7	73 s
	3	infeasible	< 1 s	infeasible	< 1 s	10	< 1 s
	4	infeasible	< 1 s	infeasible	< 1 s	11	< 1 s
	5	8	< 1 s	11	< 1 s	11	< 1 s
d^{max}	00:30	11	< 1 s	11	< 1 s	11	1 s
	01:00	10	< 1 s	11	< 1 s	11	1 s
	02:00	8	< 1 s	11	< 1 s	11	< 1 s
	03:00	5	< 1 s	9	< 1 s	9	1 s

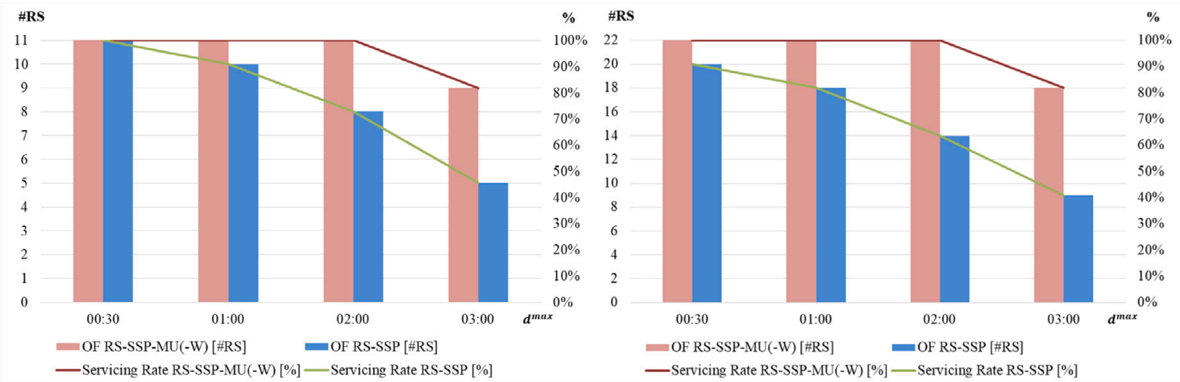

Fig. 7. Impact of d^{max} with a 30-minutes headway (left) and a 15-minutes headway (right).

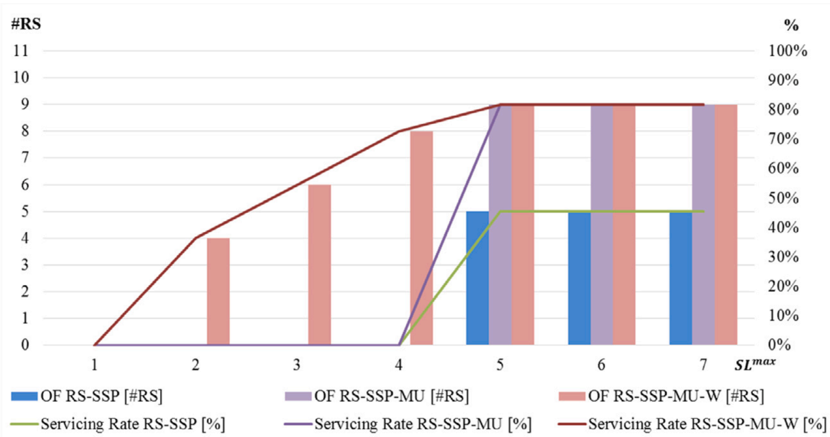

Fig. 8. Impact of SL^{max} with d^{max} of 3 h.

enhance results. As shown for the case of the Sprinter train line 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 to other train lines, these critical values would need to be specified. Accordingly, supportive adaptations on the timetable or servicing efficiency can be discovered.

6. Discussion

The focus of this research is based on smaller inspections and interior cleaning tasks. More elaborate maintenance tasks are not considered in this process. The reason for this is the independent handling of organising more elaborate maintenance tasks and daily services due to differences in frequencies, work load, time consumption and locations.

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.

Due to its network perspective, the RS-SSP is a very generic model, which can be applied to railway systems with homogeneous fleets such as metro systems, tram systems, urban railways, regional railways, or to operators with type-specific SL facilities. While the RS-SSP Base Model is useful for lines operating with single vehicles, which may be applicable to tram and bus networks, the RS-SSP-MU Model may also support the planning of vehicle circulations for lines operating with multiple connected vehicles. The RS-SSP-MU-W has the highest applicability as it also allows vehicles arriving at a service location to wait until being serviced. This may be relevant in case service locations have, for instance, a low number of personnel. 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.

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 employment. 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. Also, turning times may increase due to additional (de-)coupling. Instead of quantifying this turning time increase, a minimum required turning time tt_{min} for exchanging RS units is respected (see Constraint (12)). Therefore, an RS exchange is only considered in case of sufficient turning time. 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 focus hereby lays on daily services such as smaller inspections and interior cleaning. 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.

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. Further investigations should address additional costs as the concept of exchanging RS units may lead to an increase in manpower including drivers, maintenance crew, and cleaning staff.

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