Cleaner Logistics and Supply Chain 6 (2023) 100093

Contents lists available at ScienceDirect

Cleaner Logistics and Supply Chain

journal homepage: www.journals.elsevier.com/cleaner-logistics-and-supply-chain

A rolling horizon approach for shunting operations – An emission oriented simulation study

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ARTICLE INFO

Handling Editor: Yutao Wang

Keywords:
Marshalling yard
Emissions
Shunting
Rolling horizon

ABSTRACT

Marshalling yards are nodes in rail networks to sort railcars from incoming trains to outgoing trains. To built outgoing trains in the correct sequence, railcars are shunted by shunting locomotives. Thereby, green house gas emissions are emitted as those locomotives are usually diesel powered. As the planning of shunting operations is a very complex problem, heuristics, so-called sorting strategies, are applied in practice. In this paper the effects of practically relevant sorting strategies on green house gas emissions are studied in a rolling horizon model. The rolling horizon model is used in a simulation study to investigate the effects of sorting strategies and input parameters (like the number and composition of ingoing and outgoing trains) on green house gas emissions. The results indicate that for different parameter constellations, different emission-optimal sorting strategies exist. Thus, sorting strategy selection should be done carefully depending on the operational conditions at the shunting yards.

1. Introduction

Sustainability is a major issue in transportation research, see de Dios Ortúzar (2021). Regarding the rail freight transportation the use of electric locomotives is typically in railway transportation and more eco-friendly than most other means of transport, but diesel-powered locomotives are still in use which are much less eco-friendly. Particularly in marshalling yards often diesel-powered shunting locomotives are used which produce considerable amounts of greenhouse gas (GHG) emissions. Although there are technological alternatives to diesel-powered shunting locomotives (like battery-electric or fuel-cell powered locomotives), conventional shunting locomotives are still the dominating means of transport in marshalling yards (Bundesnetzagentur, 2021). To minimize total emissions from rail transportation also GHG emissions in marshalling yards need to be considered. Next to using "l"ocomotives, shunting emissions can also be reduced by considering GHG emissions in shunting operations planning, i.e., when planning how to sort and schedule railcars.

Railcar sorting at shunting yards aims at assembling railcars in the correct order in their dedicated outbound trains. Railcars arrive in inbound trains and are assigned to the receiving tracks. A "r"efers to all railcars assigned to a specific receiving track, see Fig. 1 (Boysen et al., 2012). Once a cut is complete, all railcars are decoupled and shunted by locomotives over the hump from where they roll into the classification tracks (so-called ")". Usually, on each classification track one outbound train is built. If after humping the sequence of railcars assigned to a classification track does not match the corresponding outbound train's target configuration, the railcars have to be "("also called ")". I.e., all railcars assembled on a classification track are moved back to the receiving area and humped again. Usually, railcars have to be humped multiple times before all outbound trains are assembled completely and correctly as usually the sequences of incoming railcars do not match the required outbound sequences.

In general marshalling yards consist of receiving, classification and departure tracks for the arrival of incoming trains, sorting railcars and building outgoing trains, respectively. In the remainder of this article the layout refers to one of the most up-to-date marshalling yard in Germany, the marshalling yard in Halle (Saale), i.e. no departure tracks are available (DB Netz AG, 2022). If no departure tracks are available, trains are sorted and built directly on classification tracks. This implies that completely assembled outbound trains block classification tracks until their departure. A different treatment of no departure tracks results in the arrival and departure on the receiving tracks, see Gestrelius (2022), A different layout comprises two yards in opposite direction, see Otto

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https://doi.org/10.1016/j.clscn.2023.100093
Received 18 November 2022; Received in revised form 18 January 2023; Accepted 29 January 2023
Available online 3 February 2023

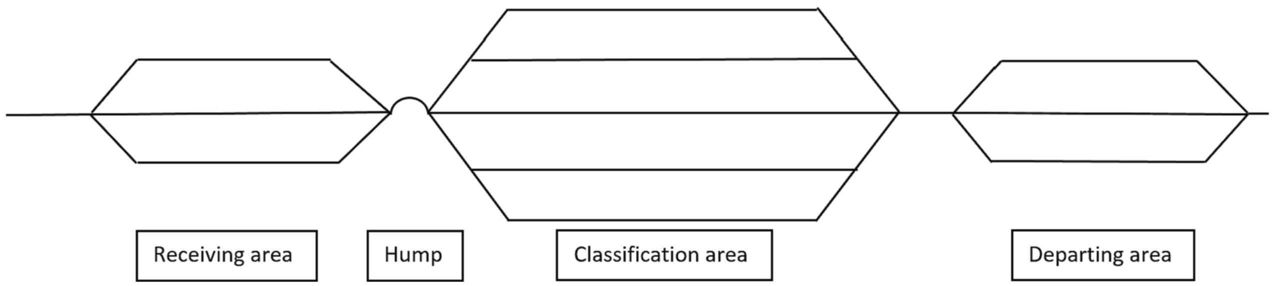

Fig. 1. Schematic layout of a marshalling yard with hump, incoming trains arrive at the receiving area, railcars are sorted in the classification area and outgoing trains are prepared for departure in the departing area.

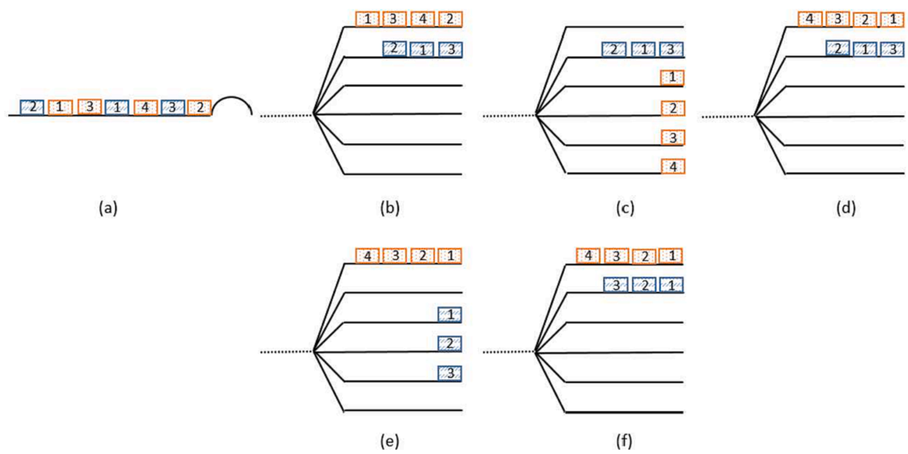

Fig. 2. Example for Sorting by train, (a) Initial situation (7 blocks, dedicated to two trains distinguished by hatching), (b) situation after initial humping, (c) 1st pullback & rehumping: split dot hatched train, (d) second pullback & rehumping: sequence dot hatched train, (e)/(f) splitting & sequencing zigzag hatched train.

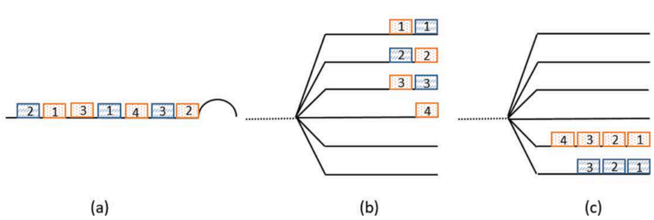

Fig. 3. Example for Sorting by block, (a) Initial situation (7 blocks, dedicated to two trains distinguished by hatching), (b) Initial humping: Sorting by block number, (c) Final result after 4 pullbacks.

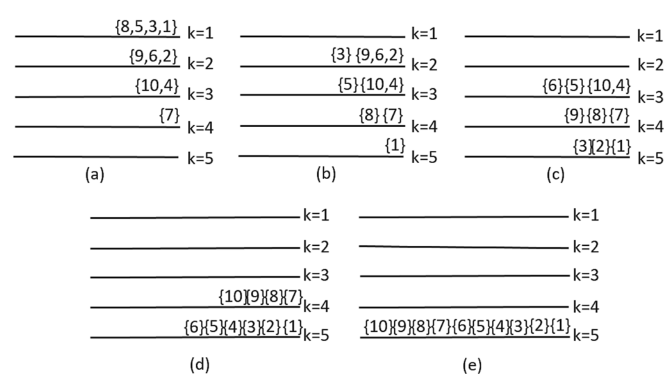

Fig. 4. Triangular Sorting: (a) Initial assignment of first 10 blocks, $k = 1, \ldots, 4$ represents the classification tracks for sorting, track $k = 5$ is used to build one outbound train, (b)–(e) Sorting blocks to classification tracks with the final outbound train in (e) on track $k = 5$.

and Pesch (2017) or two humps and no departure tracks, see Márton et al. (2009). The marshalling yard layout can also transfer to other facilities, see Jaehn et al. (2017). The authors interprete the layout of a railcar workshop as the layout of a flat yard (marshalling yard without hump).

Multi-stage sorting strategies are procedures to assign railcars to classification tracks efficiently such that e.g. rehumping is minimized, outbound trains are built on time, etc. Usually, railcars with the same destination and, thus, position in an outbound train are grouped into so-called "(Gatto et al., 2009)". Therefore, in the following we refer to the units to be sequenced in outbound trains as blocks. Another objective is to minimize the number of used tracks, see Gatto et al. (2009).

Zien and Kirschstein (2021) studies GHG emissions of shunting operations for a set of simple railcar sorting strategies. Those sorting strategies are rule-based procedures to reassemble groups of railcars from incoming trains into outbound trains, see Boysen et al. (2012), Maue (2011) and Jacob et al. (2010). Because those sorting strategies neglect the fact of time it is assumed that the whole set of incoming trains arrive in the marshalling yard before shunting starts, i.e. only one humping process is considered. In Zien and Kirschstein (2021) analytical emission functions for each sorting strategy are deduced for calculating GHG emissions. The analyses show that GHG emissions of the considered sorting strategies vary quite heavily depending on the structure of the problem instance regarding incoming and outgoing rail group composition. In this paper, the model of Zien and Kirschstein (2021) is extended by embedding the sorting strategies in a rolling horizon approach as it is common in practice. Therefore, incoming trains arrive at the marshalling yard at different points in time, i.e. humping of the incoming trains and shunting of the blocks to outgoing trains rotate. Depending on the outbound train schedules, the sorting strategies are applied in regular intervals to sort and reassemble railcars such that outbound trains are built. Additionally to the sorting strategies studied in Zien and Kirschstein (2021), parallel pullback sorting is considered which can deal with a limited number of classification tracks explicitly. For all considered sorting strategies emission functions are deduced analytically. The effects of problem instance parameters (like number and composition of incoming trains/outgoing trains, …) on a sorting strategies' total GHG emissions are analysed by systematically varying those parameters in a simulation study.

The paper is structured as follows. In Section 2 five sorting strategies are formally described. Additionally, a rolling horizon model is derived for each sorting strategy. The underlying emission model to calculate GHG emissions is briefly reviewed in Section 3. The simulation study and results are presented in Section 4. A summary of the paper and an outlook are given in Section 5.

2. Shunting operations in a rolling horizon setting

In this section the five sorting strategies *sorting by train* (SBT), *sorting by block* (SBB), *triangular sorting* (TS), *geometric sorting* (GS), and *parallel pullback sorting* (PPS) are introduced. In Subsection 2.1 shunting performance functions for each sorting strategy are presented. Adapting the performance functions of all sorting strategies to a rolling horizon approach is explained in Subsection 2.2.

2.1. Description of sorting strategies

In Gatto et al. (2009) several sorting strategies for sorting blocks in marshalling yards are proposed. One of them is *Sorting by train* (SBT). The main idea of SBT is to sort blocks on classification tracks according to their corresponding outbound train r. I.e., first all blocks of an outbound train are assigned to the same classification track irrespective of their order w. Once all blocks of the outbound train are waiting on the corresponding classification track, all railcars are pulled back and humped again. Thereby each block is assigned to an empty classification track. Finally, the blocks are pulled back one more time according to their order number w. Thus, each block is humped three times when applying SBT. Fig. 2 illustrates the procedure for an example with two trains.

Applying *Sorting by block* (SBB), see Gatto et al. (2009), means to sort all blocks to the classification tracks based on their order numbers w irrespective of their outbound train r. I.e., all blocks with the same order number are shunted to the same classification track. Subsequently, the blocks are pulled back sequentially starting with blocks $w = 1$. When rehumping, each outbound train is assigned to a classification track and the corresponding blocks are shunted accordingly. Thus, each block is humped twice. An example is displayed in Fig. 3.

SBT and SBB are simple sorting rules, but require many classification tracks if the number of blocks or the number of outbound trains is large. In Gatto et al. (2009) and Daganzo et al. (1983) a more complex method, called *Triangular sorting* (TS), can be found which requires less classification tracks.

The basic idea of TS is to sort blocks regarding a triangular sorting plan, see (a) to (d) in Fig. 4. For this purpose the number of blocks for each track has to be determined. Blocks of outgoing trains $r = 1, \dots, m$ are numbered from 1 to n_r and hence, $\widetilde{w}_{max} = \{n_r | r = 1, \dots, m\}$ denotes the highest block number over all outgoing trains, while k denotes the index of the classification tracks and $\widetilde{\mathscr{W}}_k^{TS}$ denotes the set of blocks assigned to classification track k, e.g. for $\widetilde{w}_{max} = 10$ the initially shunted blocks to track $k = 2$ are blocks 2, 6 and 9. In TS, similar to SBB, blocks are assigned to classification tracks based on their order (irrespective of their outbound train). Blocks are assigned to $\widetilde{\mathscr{W}}_k^{TS}$ according to the following scheme

$$\widetilde{\mathscr{W}}_k^{TS} = \begin{cases} \emptyset & \text{for } \widetilde{w}_{max} < \frac{k(k-1)}{2}+1 \\ \frac{k\cdot(k-1)}{2}+1 & \text{for } \frac{k(k-1)}{2}+1 \leqslant \widetilde{w}_{max} < \frac{k(k-1)}{2}+1+2k \\ \frac{k\cdot(k-1)}{2}+1, g_2^k, \dots, g^k_{\widetilde{j}_k^{TS}} & \text{for } \frac{k(k-1)}{2}+1+2k \leqslant \widetilde{w}_{max} \end{cases} \tag{1}$$

whereby

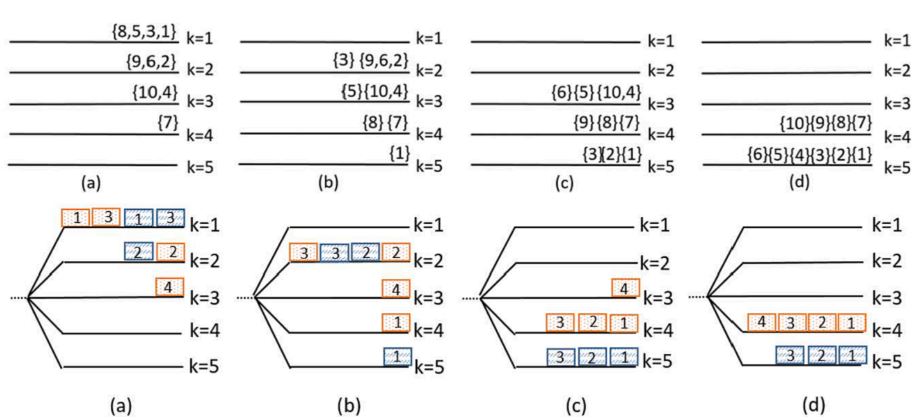

Fig. 5. Example for TS/GS: (a) Initial humping (7 blocks, dedicated to two trains distinguished by hatching), $k = 1, 2, 3$ represents the classification tracks for sorting, $k = 4, 5$ are used to build two outbound trains, (b)–(d) Sorting regarding general scheme of TS/GS, see Fig. 4 or Fig. 6, (d) Final result after 3 pullbacks.

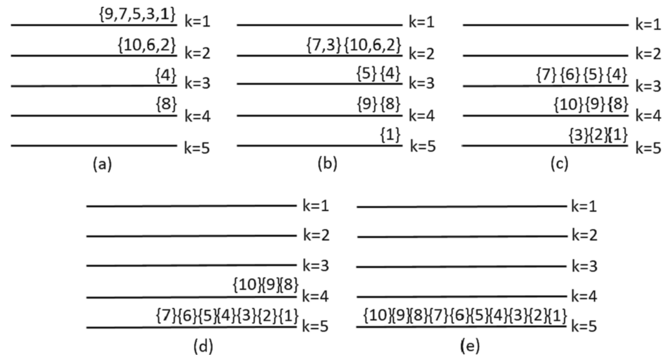

Fig. 6. Geometric Sorting: (a) Initial assignment of first 10 blocks, $k = 1, \ldots, 4$ represents the classification tracks for sorting, track $k = 5$ is used to build one outbound train, (b)–(e) Sorting blocks to classification tracks with the final outbound train in (e) on track $k = 5$.

$$g_j^k = \frac{k\cdot(k-1)}{2} + j\cdot k + 1 + \frac{(j-1)\cdot(j-2)}{2} \tag{2}$$

and

$$\bar{j}_k^{TS} = \lfloor -k + \frac{3}{2} + \frac{\sqrt{-8\cdot k - 7 + 8\cdot\widetilde{w}_{max}}}{2} \rfloor \tag{3}$$

Determining the last block g_s^k which can be shunted on track k for a given maximum block number $\widetilde{w}_{max}$ results in calculating index $s \in \mathrm{R}_+$ such that $g_s^k - \widetilde{w}_{max} = 0$ holds. The result s is not applicable in practice because only integer indices, i.e. integer block numbers, are applicable. Hence, $\bar{j}_k^{TS} \in \mathbf{N}$ holds and equation $\lfloor -k + \frac{3}{2} + \frac{\sqrt{-8\cdot k-7+8\cdot\widetilde{w}_{max}}}{2} \rfloor$ is derived.

Afterwards initial humping according to the aforementioned scheme, the blocks are pulled back and humped again sequentially starting with track $k = 1$. All blocks with $w = 1$ are sorted to an empty classification track to start composing the corresponding outbound train. Each block with $w > 1$ is sequenced to the classification track which contains block $w - 1$, i.e. to a classification track on which blocks are pull backed later or to a classification track on which the outgoing train is built.

Note that this implies that each block is rehumped at most twice. Fig. 4 illustrates the general assignment for the first 10 blocks and in Fig. 5 can be found an example with two trains (zigzag and dot hatched).

Geometric Sorting (GS), see Boysen et al. (2012) and Gatto et al. (2009), is similar to TS and mainly differs in the blocks' assignment scheme.

The initial assignment of blocks to classification tracks follows a geometric distribution as follows

$$\widetilde{\mathscr{W}}_k^{GS} = \bigcup_{j=0}^{\bar{j}_k^{GS}} \{2^{k-1} + 2^k\cdot j\} \tag{4}$$

The maximum number of blocks assigned to track k is

$$\bar{j}_k^{GS} = \lfloor \frac{\widetilde{w}_{max} - 2^{k-1}}{2^k} \rfloor \tag{5}$$

where $\widetilde{w}_{max}$ denotes the maximum index of all blocks again. The proof of $\bar{j}_k^{GS}$ is similar to the proof of (3).

Due to the geometric block assignment, typically less classification tracks are occupied by GS than by TS, but blocks are pulled back more frequently. Similar to TS, the blocks are pulled back sequentially starting with track $k = 1$. Again, the blocks with $w = 1$ are shunted to an empty classification track to start composing an outbound train. Other blocks are shunted to their corresponding outbound train or to the classification track which holds its direct predecessor. Fig. 6 illustrates the general assignment of blocks to classification tracks for GS and in Fig. 5 can be found an example with two outgoing trains.

Parallel Pullback sorting (PPS) is a sorting strategy which can build trains with a predetermined number of classification tracks $\bar{k}$. If the sequence of blocks in the incoming trains is taken into consideration PPS includes “.” The strategy is described in Gatto et al. (2009) and Dahlhaus et al. (2000) for one incoming and one outgoing train and with or without presortedness. Because PPS with presortedness is at least equal or better than PPS without presortedness the following explanations are referred to PPS with presortedness. Also the procedure is extended for more than one incoming and one outgoing train. Adapting the procedure to multiple incoming trains is straightforward. For adapting to multiple outgoing trains allows multiple options. One option is to number the blocks of each outgoing train r from 1 to n_r which is applied in the rolling horizon approach in Subsection 2.2.

The blocks of an incoming train are assigned to batches of blocks $B_{b,r}^{pss}$ in sorting step $pss = 1, 2, \ldots$ for batch $b = 1, 2, \ldots$ and outgoing train r. This assignment can be found in the procedure below. To apply PPS a preprocessing step is necessary. The preprocessing step involves creating batches $B_{b,r}^0$ $(b = 1, 2, \ldots)$, where all relatively sequenced blocks in the incoming train are assigned to the same batch. Afterwards the following sorting steps $pss = 1, 2, \ldots$ are repeated until the correct block sequences are reached on the classification tracks:

1. Blocks on the receiving tracks are humped into the classification tracks depending on their assignment to batches. Batch $B_{b,r}^{pss-1}$ is assigned to classification track $1 + ((b-1) \bmod \bar{k})$.

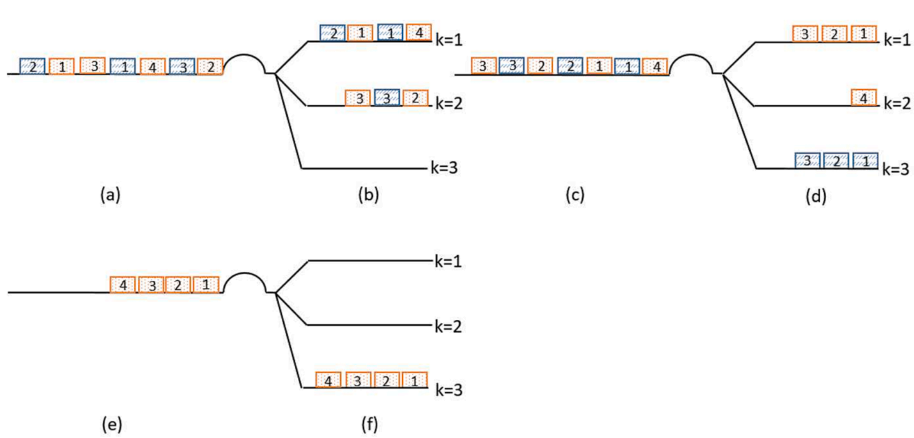

Fig. 7. Parallel Pullbacks with presortedness applied to two classification tracks for sorting $k = 1, 2$ and one track for departure $k = 3$, (a) one inbound train has to be shunted to two outgoing trains; assembling of initial batches: dot hatched train (= train 1) $B_{1,1}^0 = \{1\}$, $B_{2,1}^0 = \{2, 3\}$, $B_{3,1}^0 = \{4\}$, zigzag hatched train (= train 2) $B_{1,2}^0 = \{1, 2\}$, $B_{2,2}^0 = \{3\}$, (b) Push batchelements of each outgoing train into their designated classification track, (c) Pullback of the second ($k = 2$) and afterwards the first ($k = 1$) classification track; assembling of batches by combining each two batches: dot hatched train $B_{1,1}^1 = \{1, 2, 3\}$, $B_{2,1}^1 = \{4\}$, zigzag hatched train $B_{1,2}^1 = \{1, 2, 3\}$, (d) Push batchelements into their designated classification track; blocks of the zigzag hatched train to $k = 3$ for departure, (e) Pullback of the second ($k = 2$) and afterwards the first ($k = 1$) classification track to get the final composition, (f) humping of the blocks to $k = 3$ for departure of the dot hatched train.

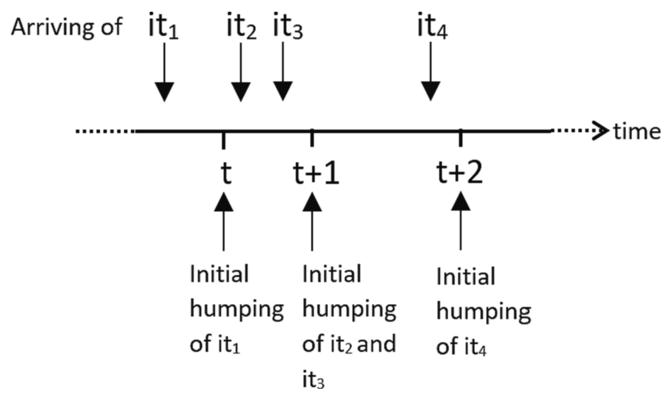

Fig. 8. Example for arriving of four incoming trains (it) and their initial humping at the beginning of period t, t + 1 and t + 2. After initial humping sorting of blocks is taken place until period ends.

2. Pull back each classification track in descending order ($\bar{k}, \bar{k}-1, \ldots, 2, 1$) into the receiving tracks.
3. Determine $B^{pss}_{b,r} = \bigcup_{i=1+(b-1)\cdot\bar{k}^{pss}}^{b\cdot\bar{k}^{pss}} B^{0}_{i,r}$ for $b = 1, 2, \ldots$

For an example of PPS with presortedness, see Fig. 7. If n is the number of blocks of the incoming train, the number of needed sorting steps is $\lceil log_{\bar{k}} n \rceil$ which refers to PPS without presortedness. If d is the number of batches which are necessary for the presorted blocks, the number of needed sorting steps is $\lceil log_{\bar{k}} d \rceil$. Inequality $n \geqslant d$ implies $\lceil log_{\bar{k}} n \rceil \geqslant \lceil log_{\bar{k}} d \rceil$, i.e. if presortedness is included the number of sorting steps is less or equal compared to the procedure without presortedness.

2.2. Rolling horizon approach in a shunting environment

The sorting strategies described in Subsection 2.1 generate a sorting plan for a given set of outbound trains to be built from a given set of inbound trains without considering time. In practice, however, sorting is conducted perpetually in certain time intervals depending on the train schedules. This implies that the sets of inbound and outbound trains are incomplete and change dynamically over time. To study the effects of those sorting strategies in such a rolling horizon environment requires to deduce generalized forms of performance functions for each sorting strategy which ables to deal with incomplete train sets already waiting for completion or humping.

Definitions and the general rolling horizon procedure are described in Subsubsection 2.2.1. Specific generalized performance functions for each sorting strategy are deduced in the subsequent subsections.

2.2.1. General procedure and definitions

In the following, a multi-period planning horizon is assumed which consists of p periods. If all blocks of an outgoing train have arrived in the marshalling yard in a certain period, the outgoing train is called “.” Otherwise, the outgoing train is called “.” If R denotes the set of all outgoing trains $\mathscr{R}_t \in \mathscr{R}$ marks the set of outgoing trains in the marshalling yard in period t. Let $\mathscr{W}$ be the set of blocks and $v_{w,r}$ the number of railcars in block w of train r. At the beginning of a period, all blocks of all incoming trains are humped to the classification tracks which is called “.” At the beginning of period $t = 1$ there are no blocks on the classification tracks. In each period a termination criterion determines the transition to a new period, i.e. shunting of blocks is stopped and a new period starts with initial humping of the newly arrived trains. This termination criterion $\bar{g}_t$ corresponds to a step for SBT, a track for SBB, TS and GS and a sorting step for PPS and is to be determined initially.

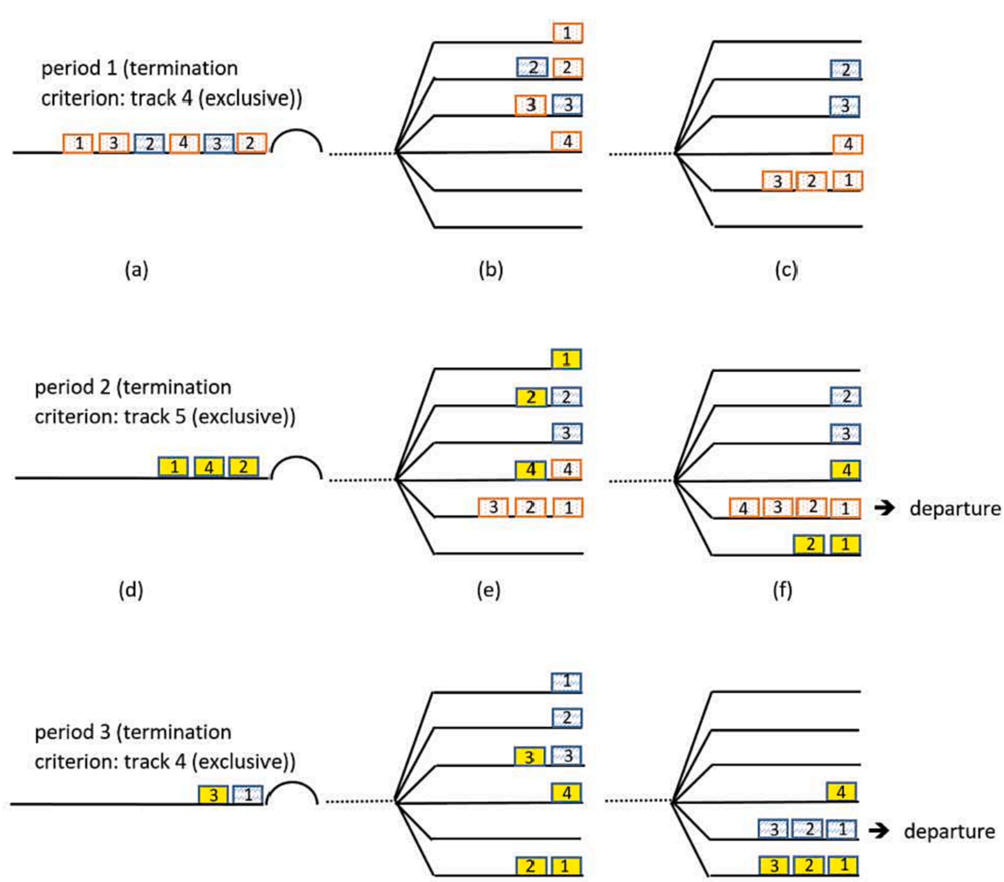

Fig. 9. Rolling horizon with 3 periods, 3 trains and the sorting procedure SBB, (a) incoming blocks of the dot hatched (construtable) and zigzag hatched (not constructable) train, (b) shunting blocks w.r.t. SBB, (c) pulling back track 1 to 3 without track 4, (d) incoming blocks of the continously hatched (not constructable) train, (e) shunting blocks w.r.t. SBB, (f) pulling back track 1 to 4, i.e. afterwards the dot hatched train departs, (g) missing blocks of the continously hatched and zigzag hatched blocks arrive in the marshalling yard, (h) shunting blocks w.r.t. SBB, (i) pulling back track 1 to 3 without track 4, i.e. afterwards the zigzag hatched train departs and the continously hatched train remains in the marshalling yard at the end of the planning horizon.

Table 1
Best sorting strategies for varying expected numbers of blocks in outgoing trains, numbers of outgoing trains and numbers of incoming trains, b – Sorting-by-block (SBB), t – Sorting-by-Train (SBT).

a) $\lambda = 5$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	t	t	t	t	t	t	t
50	b	b	t	t	t	t	t	t	t	t
60	b	t	t	t	t	t	t	t	t	t
70	b	t	t	t	t	t	t	t	t	t
80	b	t	t	t	t	t	t	t	t	t
90	t	t	t	t	t	t	t	t	t	t
100	t	t	t	t	t	t	t	t	t	t

b) $\lambda = 10$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	t	t	t	t	t	t
70	b	b	t	t	t	t	t	t	t	t
80	b	b	t	t	t	t	t	t	t	t
90	b	t	t	t	t	t	t	t	t	t
100	b	t	t	t	t	t	t	t	t	t

c) $\lambda = 15$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	t	b	t	b

d) $\lambda = 20$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

e) $\lambda = 25$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

f) $\lambda = 30$

Table 1 (*continued*)

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

The general procedure of the five sorting strategies regarding the rolling horizon is as follows. First, initial humping is conducted, i.e. each incoming train is humped on the classification tracks based on the chosen sorting strategy, see subsubsection 2.1. Afterwards, the chosen sorting strategy is applied iteratively but adapted to deal with the blocks left over from the previous period. I.e. a sorting strategy with a rolling horizon adaption is applied to the blocks in the classification tracks. An example which visualizes the course of time can be found in Fig. 8. While shunting, blocks left over from previous periods and initially humped blocks newly arrived are taken into account at the same time. If track k which includes blocks of not constructable trains is pulled back, the blocks of not constructable trains are shunted to track k again. Later, emissions are calculated for each applied sorting strategy. Therefore, it is necessary to investigate the number of railcars for each pullback. For this purpose the so-called "f"or each of the five sorting strategies is derived, i.e. a set of numbers (= amount of railcars) per pullback is determined in period t. An example of shunting blocks in three subsequent periods can be found in Fig. 9.

2.2.2. *Rolling horizon approach for Sorting-by-train*

SBT is insensitive to the rolling horizon approach in the following way. The SBT sorting strategy is only applied to constructable trains. Blocks of not constructable trains remain on their assigned classification tracks and, therefore, do not influence shunting operations of constructable trains. Each constructable train r is processed by the following steps:

- $s_{r,0}$: Pull back and roll in all blocks of constructable train r
- $s_{r,1}$: Pull back and roll in railcars of blocks 1

  ⋮
- s_{r,n_r}: Pull back and roll in railcars of blocks n_r.

where n_r denotes the number of blocks of train r.

Outgoing trains can be built in arbitrary sequences until period t ends, i.e. if $r_{(1)}, r_{(2)}, \dots$ marks the construction sequence of the outgoing trains, a list of shunting steps can be defined as follows

$$L = \left(s_{r_{(1)},0}, s_{r_{(1)},1}, \dots, s_{r_{(1)},n_{r_{(1)}}}, s_{r_{(2)},0}, s_{r_{(2)},1}, \dots, s_{r_{(2)},n_{r_{(2)}}}, \dots\right). \tag{6}$$

When period t ends while step $s \in L$ is conducted, the building of the corresponding train r' can be continued in period $t+1$ in step $s+1 (= \bar{g}_t)$ where $\bar{g}_t$ marks the (excluded) termination criterion of SBT in period t. Shunting of train $r' \in \mathscr{R}$ can be continued in period $t+1$ without consideration of incoming blocks because classification tracks with blocks of constructable trains receive no more blocks in further periods and hence, do not change over time.

Therefore, sorting performance of SBT can be derived without consideration of period t by

$$SP^{SBT}\left(\mathscr{W}, \mathscr{R}\right) = \bigcup_{r \in \mathscr{R}} \left\{ \sum_{w=1}^{n_r} v_{w,r}, v_{1,r}, \dots, v_{n_r,r} \right\}. \tag{7}$$

2.2.3. *Rolling horizon approach for sorting-by-block*

Applying SBB in a rolling horizon approach requires additional as-

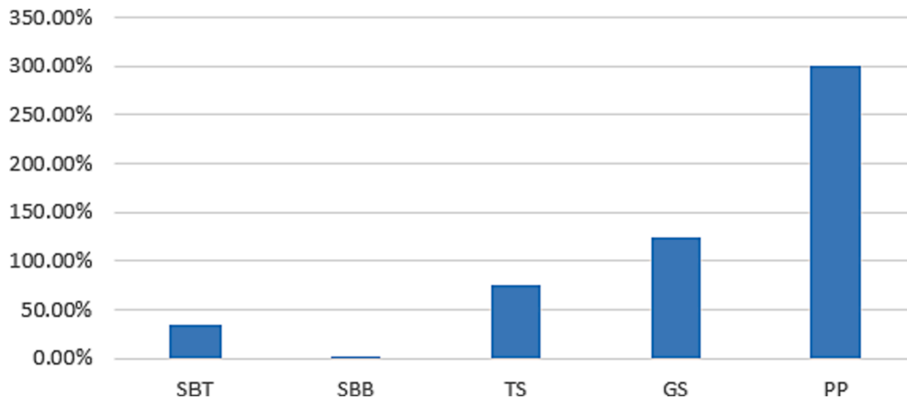

Fig. 10. Average deviation (in %) from the best sorting strategy.

Table 2
Best sorting strategies w.r.t. minimal emissions for varying expected numbers of blocks in outgoing trains, numbers of outgoing trains and numbers of incoming trains, interval of periods of blocks comprises only two sequential periods, b – Sorting-by-Block (SBB), x – Parallel Pullbacks sorting (PPS).

g) $\lambda = 10$

ot\it	10	20	30	40	50	60	70	80	90	100
10	x	x	x	x	x	x	x	x	x	x
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

h) $\lambda = 20$

ot\it	10	20	30	40	50	60	70	80	90	100
10	x	x	x	x	x	x	x	x	x	x
20	b	b	x	x	x	x	x	x	x	x
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

i) $\lambda = 30$

ot\it	10	20	30	40	50	60	70	80	90	100
10	x	x	x	x	x	x	x	x	x	x
20	b	b	b	b	b	x	b	x	b	x
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

sumptions. In each period the sorting process starts (after initial humping) with the first classification track, i.e. the track where blocks with number $w = 1$ are collected. If one or more classification tracks contain only blocks which can not be shunted to their designated departing tracks, all blocks of the considered classification tracks are not shunted.

To express the sorting performance of SBB in a rolling horizon approach sets of blocks are defined and combined. $\mathscr{W}_{t,0}^{SBB,r}$ defines the set of blocks of the outgoing train r which arrive in the marshalling yard in period $t-1$. Therefore, they are available for initial humping in period t. Blocks waiting on the classification tracks in period t are summarized in $\mathscr{W}_{t}^{SBB,r}$. $\mathscr{W}_{t}^{SBB,r,ex}$ denotes the set of blocks of train r on the corresponding departing track at the beginning of period t.

Thus, the set of blocks of train r humped into the classification tracks in period t is defined by $\mathscr{W}_{t}^{SBB,r,in} = \mathscr{W}_{t,0}^{SBB,r} \cup \mathscr{W}_{t}^{SBB,r}$. The set of blocks of train r shunted from classification to departing tracks in period t is denoted by $\mathscr{W}_{t}^{SBB,r,out}$ and is constructed as follows

$$\begin{aligned} \mathscr{W}_{t}^{SBB,r,out} = \; & \left\{ w \middle| w^{v} \in \mathscr{W}_{t}^{SBB,r,ex} \cup \left(\mathscr{W}_{t}^{SBB,r} \cup \mathscr{W}_{t,0}^{SBB,r} \right) \backslash \left\{ \overline{g}_t, \overline{g}_t + 1, \ldots \right\} \right. \\ & \left. \forall w^{v} = 0, 1, \ldots, w \right\} \backslash \mathscr{W}_{t}^{SBB,r,ex} \end{aligned} \tag{8}$$

Thereby, block w is shunted to the departing tracks, if all predecessor blocks w^{v} are already on the departing tracks ($\mathscr{W}_{t}^{SBB,r,ex}$) or they are shunted from the classification tracks to the departing tracks in period t. I.e. predecessor block w^{v} is already on the classification tracks at the beginning of period t ($\mathscr{W}_{t}^{SBB,r}$) or is initially humped in period t ($\mathscr{W}_{t,0}^{SBB,r}$). In the latter case, blocks are not shunted if the termination criterion is exceeded. I.e. all blocks which are equal or exceed $\overline{g}_t$ are not shunted in period t, but wait for further processing in subsequent periods.

At the beginning of period t blocks on the classification tracks ($W_{t}^{SBB,r}$) can be expressed by blocks on the classification tracks ($W_{t}^{SBB,r,in}$) without outgoing blocks ($W_{t}^{SBB,r,out}$) of the previous period $t-1$ through

$$W_{t}^{SBB,r} = \begin{cases} \varnothing & \text{for } t = 1 \\ W_{t-1}^{SBB,r,in} \backslash W_{t-1}^{SBB,r,out} & \text{for } t > 1 \end{cases}. \tag{9}$$

Blocks of train $r \in \mathscr{R}$ on the departing tracks at the beginning of period t can be formulated by

$$W_{t}^{SBB,r,ex} = \begin{cases} \varnothing & \text{for } t = 1 \\ W_{t-1}^{SBB,r,ex} \cup W_{t-1}^{SBB,r,out} & \text{for } t > 1 \end{cases}, \tag{10}$$

i.e. blocks on the departure tracks in period $t-1$ ($W_{t-1}^{SBB,r,ex}$) and outgoing blocks in period $t-1$ ($W_{t-1}^{SBB,r,out}$). Finally, the sorting performance for SBB can be expressed by

$$SP_{t}^{SBB}\left(\mathscr{W}_{t}, \mathscr{R}_{t} \right) = \bigcup_{w=1,\ldots,\overline{g}_t-1} \left\{ \sum_{r \in \mathscr{R}_t \middle| w \in W_{t,0}^{SBB,r} \cup W_{t}^{SBB,r}} v_{w,r} \right\} \tag{11}$$

i.e. the set of initially humped railcars ($W_{t,0}^{SBB,r}$) and already existing railcars on the classification tracks ($W_{t}^{SBB,r}$) up to the excluded termination criterion $\overline{g}_t$ is determined for (not) constructable trains $r \in \mathscr{R}_t$ in period t.

Table 3
Best sorting strategies w.r.t average number of pulled back railcars for varying expected numbers of blocks in outgoing trains, numbers of outgoing trains and numbers of incoming trains, b – Sorting-by-block (SBB), t – Sorting-by-Train (SBT).

a) $\lambda = 5$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	t	t	t	t	t	t	t	t
40	b	t	t	t	t	t	t	t	t	t
50	b	t	t	t	t	t	t	t	t	t
60	b	t	t	t	t	t	t	t	t	t
70	b	t	t	t	t	t	t	t	t	t
80	b	t	t	t	t	t	t	t	t	t
90	b	t	t	t	t	t	t	t	t	t
100	b	t	t	t	t	t	t	t	t	t

b) $\lambda = 10$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	t	b	t	t	t	t	t
30	b	t	t	t	t	t	t	t	t	t
40	b	t	t	t	t	t	t	t	t	t
50	b	t	t	t	t	t	t	t	t	t
60	b	t	t	t	t	t	t	t	t	t
70	b	t	t	t	t	t	t	t	t	t
80	b	t	t	t	t	t	t	t	t	t
90	b	t	t	t	t	t	t	t	t	t
100	b	t	t	t	t	t	t	t	t	t

c) $\lambda = 15$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	t	b	b	t	t
30	b	b	t	t	t	t	t	t	t	t
40	b	t	t	t	t	t	t	t	t	t
50	b	t	t	t	t	t	t	t	t	t
60	b	t	t	t	t	t	t	t	t	t
70	b	t	t	t	t	t	t	t	t	t
80	b	t	t	t	t	t	t	t	t	t
90	b	t	t	t	t	t	t	t	t	t
100	b	t	t	t	t	t	t	t	t	t

d) $\lambda = 20$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	t	t	b	b	t	t	t
40	b	b	t	t	t	t	t	t	t	t
50	b	b	t	t	t	t	t	t	t	t
60	b	b	t	t	t	t	t	t	t	t
70	b	t	t	t	t	t	t	t	t	t
80	b	t	t	t	t	t	t	t	t	t
90	b	t	t	t	t	t	t	t	t	t
100	b	t	t	t	t	t	t	t	t	t

e) $\lambda = 25$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	t	b	b	t	t
40	b	b	b	b	t	t	t	t	t	t
50	b	b	b	t	t	t	t	t	t	t
60	b	b	t	t	t	t	t	t	t	t
70	b	b	t	t	t	t	t	t	t	t
80	b	b	t	t	t	t	t	t	t	t
90	b	b	t	t	t	t	t	t	t	t
100	b	b	t	t	t	t	t	t	t	t

f) $\lambda = 30$

Table 3 (*continued*)

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	t	t	b	t	t	t
50	b	b	b	t	t	t	t	t	t	t
60	b	b	b	t	t	t	t	t	t	t
70	b	b	t	t	t	t	t	t	t	t
80	b	b	t	t	t	t	t	t	t	t
90	b	b	t	t	t	t	t	t	t	t
100	b	b	t	t	t	t	t	t	t	t

Table 4
Best sorting strategies w.r.t average number of pulled back railcarss for varying expected numbers of blocks in outgoing trains, numbers of outgoing trains and numbers of incoming trains, interval of periods of blocks comprises only two sequential periods, b – Sorting-by-Block (SBB)

g) $\lambda = 10$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

h) $\lambda = 20$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

i) $\lambda = 30$

ot\it	10	20	30	40	50	60	70	80	90	100
10	b	b	b	b	b	b	b	b	b	b
20	b	b	b	b	b	b	b	b	b	b
30	b	b	b	b	b	b	b	b	b	b
40	b	b	b	b	b	b	b	b	b	b
50	b	b	b	b	b	b	b	b	b	b
60	b	b	b	b	b	b	b	b	b	b
70	b	b	b	b	b	b	b	b	b	b
80	b	b	b	b	b	b	b	b	b	b
90	b	b	b	b	b	b	b	b	b	b
100	b	b	b	b	b	b	b	b	b	b

2.2.4. *Rolling horizon approach for Triangular sorting/Geometric sorting*

The sorting performances for TS and GS can be derived simultaneously because they only differ in several input factors. The derived formulas are more complex compared to SBB and need more assumptions. Shunting starts with the first classification track in each period. If a classification track has no blocks or only blocks which can not be shunted, the blocks are not pulled back. Each outgoing train $r \in \mathscr{R}$ contains blocks numbered from 1 to n_r. After initial humping, blocks can be shunted to their designated departure track without detours on other classification tracks. Blocks remain on the classification tracks if predecessor blocks are not on the classification or departing tracks.

The termination criterion $\overline{g}_t$ corresponds to a classification track

Table 5
Average technical parameters of DB railcar types.

railcar type	Average tare weight	Average load limit
E (Open railcars)	23.6	63.0
F (Open hopper railcars)	31.3	68.7
H (High-capacity sliding-wall covered railcars)	28.1	42.8
K (Flat railcars with 2 axles)	25.8	41.3
L (Car transporter units)	36.5	35.5
R (Bogie flat railcars)	26.6	63.3
S (Six-axle bogie flat railcars)	29.5	75.6
S (Bogie coil railcars)	26.8	68.9
S (Bogie flat railcars with cargo ratchet straps)	25.0	63.0
T (Covered bulk railcars)	22.9	60.0
T (Railcar with opening roof)	23.3	66.5

(excluded) where shunting in period t ends. The total amount of necessary tracks to shunt outgoing train r is given by $\overline{k}^{TS,r} = \lfloor\sqrt{2\cdot n_r - \frac{7}{4}} + \frac{1}{2}\rfloor$ for TS, see Daganzo et al. (1983) and $\overline{k}^{GS,r} = \lfloor\log_2 n_r\rfloor + 1$ for GS, see Gatto et al. (2009). Thus, the maximum number of classification tracks can be derived as $\overline{k}^{TS/GS} = \max_{r\in R}\overline{k}^{TS/GS,r}$. For each classification track, sets of sequenced blocks can be determined, e.g. blocks $\{2,3\}$ or $\{6,7\}$ on classification track 2. These sets consist of blocks which are shunted throughout initial humping, e.g. 2 or 6 and successor blocks of predecessor classification tracks, e.g. 3 or 7. Shunted blocks throughout initial humping can be expressed by

$$\widetilde{W}^{TS}_{k,j} = \begin{cases} \left\{\dfrac{k\cdot(k-1)}{2} + 1\right\} & \text{for } j = 1 \\ \left\{\dfrac{k\cdot(k-1)}{2} + 1 + j\cdot k + \dfrac{(j-1)(j-2)}{2}\right\} & \text{for } j > 1 \end{cases} \quad (12)$$

for TS and $\widetilde{\mathscr{W}}^{GS}_{k,j} = \{2^{k-1} + 2^k\cdot(j-1)\}$ with $k,j \in \mathbb{N}_{>0}$ for GS, where k denotes the considered classification track and j the sequenced blocks set. Successor blocks can be derived as $\overline{\mathscr{W}}^{TS}_{k} = \{w \mid \overline{w}_{k-1} < w < \overline{w}_k,\ \overline{w}_k = \frac{k(k+1)}{2} + 1\}$ for TS and $\overline{\mathscr{W}}^{GS}_{k,j} = \{2^k\cdot j - i \mid i = 1,\dots,2^{k-1} - 1\}$ with k, $j \in \mathbb{N}_{>0}$ for GS. Combining initially humped blocks sets ($\widetilde{W}^{TS/GS}_{k,j}$) and successor blocks sets ($\overline{\mathscr{W}}^{TS/GS}_{k}$) results in

$$\widehat{W}^{TS}_{k,j} = \begin{cases} \emptyset & \text{for } k = 0 \\ \widetilde{W}^{TS}_{k,j} & \text{for } k > 0, j > 1 \\ \widetilde{W}^{TS}_{k,j} \cup \overline{W}^{TS}_{k} & \text{for } k > 0, j = 1 \end{cases} \quad (13)$$

for TS and

$$\widehat{W}^{GS}_{k,j} = \begin{cases} \emptyset & \text{for } k = 0 \\ \widetilde{\mathscr{W}}^{GS}_{k,j} \cup \overline{\mathscr{W}}^{GS}_{k,j} & \text{for } k > 0\ (j > 0) \end{cases} \quad (14)$$

for GS. The set of blocks of train $r \in \mathscr{R}$ on the departing tracks at the end of period t can be expressed by

$$W^{TS/GS,r,ex}_{t} = \begin{cases} \emptyset & \text{for } t = 0 \\ \left\{ w | w \in \left\{ W^{TS/GS,r,ex}_{t-1} \cup \bigcup_{k' < \overline{g}_t} W'^{TS/GS,r}_{t,k',1} \right\} \wedge w = 1,2,\dots \text{consecutively numbered} \right\} & \text{for } t > 0 \end{cases}, \quad (15)$$

i.e. the union of blocks on the departing track of the previous period $t-1$ ($W^{TS/GS,r,ex}_{t-1}$) and blocks pulled back in period t ($\bigcup_{k'<\overline{g}_t} W'^{TS/GS,r}_{t,k',1}$). The set of shunted blocks in period t can be derived as

$$W^{TS/GS,r,out}_{t,k} = \begin{cases} \emptyset, & \text{for } k \geqslant \overline{g}_t \\ \left(\bigcup_{k'>k} W'^{TS/GS,r}_{t,k'} \cup W^{TS/GS,r,ex}_{t}\right) \cap W'^{TS/GS,r}_{t,k} & \text{for } k < \overline{g}_t \end{cases}. \quad (16)$$

For classification tracks $k < \overline{g}_t$, all blocks of outgoing train r which leave track k in period t are summarized in $W^{TS/GS,r,out}_{t,k}$. This set consists of blocks which are not yet shunted on classification tracks ($\bigcup_{k'>k} W'^{TS/GS,r}_{t,k'}$) and blocks on the departing tracks ($W^{TS/GS,r,ex}_{t}$). However, these blocks are only considered if these blocks are in the set of pulled back blocks on classification track k ($W'^{TS/GS,r}_{t,k}$).

To formulate the sorting performance of TS and GS, an additional set of blocks of train r at the end of period t on classification track k is necessary. This set can be described by

$$W^{TS/GS,r}_{t,k} = \begin{cases} W^{r}_{t,0} & \text{for } k = 0 \\ \emptyset & \text{for } k > 0, t = 0 \\ W'^{TS/GS,r}_{t,k} \setminus W^{TS/GS,r,out}_{t,k} & \text{for } k > 0, t > 0 \end{cases}, \quad (17)$$

i.e. classification track $k = 0$ corresponds to the receiving track and equals the set of incoming blocks in period t. At the beginning of period $t = 1$ (i.e. at the end of period $t = 0$) there are no blocks on the classification tracks. Other combinations of $k > 0$ and $t > 0$ results in the set of pulled back blocks ($W'^{TS/GS,r}_{t,k}$) without blocks which are on further classification tracks or on the departing tracks ($W^{TS/GS,r,out}_{t,k}$), i.e. blocks on classification track k at the end of period t. Describing the consecutively numbered blocks in $W'^{TS/GS,r}_{t,k,j}$, parameter $\alpha^{TS/GS}_{k,j}$ defines the first blocks of the sequenced block set j on track k as follows

$$\alpha^{TS}_{k,j} = \begin{cases} \dfrac{k\cdot(k-1)}{2} + 1 & \text{for } j = 1 \\ \dfrac{k\cdot(k-1)}{2} + 1 + k\cdot j + \dfrac{(j-1)(j-2)}{2} & \text{for } j > 1 \end{cases} \quad (18)$$

for TS and $\alpha^{GS}_{k,j} = 2^{k-1} + 2^k(j-1)$ for GS. E.g., regarding again the sets of sequenced blocks $\{2,3\}$ and $\{6,7\}$ the first blocks are $\alpha^{TS/GS}_{2,1} = 2$ and $\alpha^{TS/GS}_{2,2} = 6$. Parameter $\alpha^{TS/GS}_{k,j}$ is used to express the set of shunted blocks of the sequenced blocks set j on track k as

$$W'^{TS/GS,r}_{t,k,j} = \begin{cases} \emptyset & \text{for } k > \overline{k}^{TS/GS,r} \\ \left\{ w | w \in \widehat{W}^{TS/GS}_{k,j} \cap \bigcup_{k' \leqslant k} W^{TS/GS,r}_{t-1,k'} \wedge w = \alpha^{TS/GS}_{k,j}, \alpha^{TS/GS}_{k,j} + 1, \dots \text{consecutively numbered} \right\} & \text{for } k \leqslant \overline{k}^{TS/GS,r} \end{cases}. \quad (19)$$

I.e. considering the intersection of theoretically blocks on track k in sequenced block set j ($\widehat{W}^{TS/GS}_{k,j}$) and the actually shunted blocks of all

Table 6
Technical parameters for shunting locomotive and railcars used in the emission model of Kirschstein and Meisel (2015).

ϵ	k	p	c^{loc}_{roll}	$c^{railcar}_{roll}$	c^{aux1}_{roll}	c^{aux2}_{roll}	c^{loc}_{air}	$c^{railcar}_{air}$	A	n_{axles}
0.4	3.15	0.1004	0.003	0.0006	0.0005	0.0006	0.8	0.218	9	4

Table 7
Total emissions (kg CO2e) for expected value of blocks = 5 (ot = number of outgoing trains, it = number of incoming trains)

ot\it	10		20		30		40		50		60		70		80		90		100	
10	326	SBB	333	SBB	334	SBB	340	SBB	349	SBB	344	SBB	343	SBB	348	SBB	356	SBB	356	SBB
20	730	SBB	754	SBB	782	SBB	804	SBB	778	SBB	824	SBB	814	SBB	799	SBB	818	SBB	821	SBB
30	1173	SBB	1251	SBB	1276	SBB	1314	SBB	1333	SBB	1346	SBB	1356	SBB	1351	SBB	1367	SBB	1357	SBB
40	1671	SBB	1807	SBB	1813	SBB	1867	SBT	1867	SBT	1866	SBT	1854	SBT	1849	SBT	1857	SBT	1855	SBT
50	2216	SBB	2371	SBB	2378	SBT	2358	SBT	2347	SBT	2345	SBT	2338	SBT	2337	SBT	2327	SBT	2325	SBT
60	2824	SBB	2914	SBT	2864	SBT	2830	SBT	2832	SBT	2807	SBT	2804	SBT	2798	SBT	2793	SBT	2798	SBT
70	3465	SBB	3435	SBT	3364	SBT	3330	SBT	3318	SBT	3294	SBT	3284	SBT	3281	SBT	3267	SBT	3267	SBT
80	4228	SBB	3969	SBT	3864	SBT	3832	SBT	3784	SBT	3768	SBT	3755	SBT	3742	SBT	3743	SBT	3744	SBT
90	4866	SBT	4501	SBT	4384	SBT	4344	SBT	4261	SBT	4265	SBT	4244	SBT	4237	SBT	4223	SBT	4227	SBT
100	5496	SBT	5045	SBT	4899	SBT	4817	SBT	4778	SBT	4746	SBT	4722	SBT	4702	SBT	4704	SBT	4693	SBT

Table 8
Total emissions (kg CO2e) for expected value of blocks = 10 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	314	SBB	346	SBB	365	SBB	365	SBB	370	SBB	372	SBB	372	SBB	384	SBB	369	SBB	378	SBB
20	691	SBB	755	SBB	809	SBB	815	SBB	807	SBB	823	SBB	833	SBB	855	SBB	851	SBB	870	SBB
30	1134	SBB	1243	SBB	1263	SBB	1362	SBB	1357	SBB	1381	SBB	1352	SBB	1381	SBB	1407	SBB	1416	SBB
40	1608	SBB	1750	SBB	1802	SBB	1942	SBB	1952	SBB	1912	SBB	1951	SBB	1971	SBB	2010	SBB	2006	SBB
50	2132	SBB	2380	SBB	2461	SBB	2557	SBB	2553	SBB	2570	SBB	2612	SBB	2631	SBB	2625	SBB	2634	SBB
60	2700	SBB	2955	SBB	3109	SBB	3133	SBB	3212	SBT	3208	SBT	3200	SBT	3192	SBT	3187	SBT	3173	SBT
70	3276	SBB	3635	SBB	3812	SBT	3773	SBT	3759	SBT	3748	SBT	3732	SBT	3726	SBT	3731	SBT	3712	SBT
80	3966	SBB	4345	SBB	4388	SBT	4328	SBT	4322	SBT	4293	SBT	4279	SBT	4268	SBT	4257	SBT	4260	SBT
90	4698	SBB	5094	SBT	4951	SBT	4920	SBT	4847	SBT	4837	SBT	4815	SBT	4802	SBT	4806	SBT	4805	SBT
100	5402	SBB	5688	SBT	5539	SBT	5454	SBT	5421	SBT	5415	SBT	5372	SBT	5353	SBT	5345	SBT	5344	SBT

Table 9
Total emissions (kg CO2e) for expected value of blocks = 15 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	334	SBB	359	SBB	371	SBB	383	SBB	388	SBB	388	SBB	389	SBB	389	SBB	390	SBB	388	SBB
20	690	SBB	762	SBB	804	SBB	809	SBB	832	SBB	857	SBB	815	SBB	850	SBB	863	SBB	870	SBB
30	1129	SBB	1210	SBB	1269	SBB	1307	SBB	1333	SBB	1334	SBB	1376	SBB	1377	SBB	1389	SBB	1384	SBB
40	1576	SBB	1752	SBB	1843	SBB	1881	SBB	1892	SBB	1895	SBB	1919	SBB	1950	SBB	1911	SBB	1941	SBB
50	2137	SBB	2254	SBB	2349	SBB	2417	SBB	2488	SBB	2498	SBB	2543	SBB	2566	SBB	2575	SBB	2577	SBB
60	2633	SBB	2895	SBB	2933	SBB	3095	SBB	3144	SBB	3128	SBB	3173	SBB	3184	SBB	3131	SBB	3242	SBB
70	3232	SBB	3517	SBB	3606	SBB	3810	SBB	3761	SBB	3812	SBB	3875	SBB	3873	SBB	3876	SBB	3910	SBB
80	3852	SBB	4118	SBB	4244	SBB	4448	SBB	4526	SBB	4482	SBB	4551	SBB	4574	SBB	4671	SBB	4662	SBB
90	4516	SBB	4854	SBB	5090	SBB	5083	SBB	5283	SBB	5242	SBB	5448	SBB	5403	SBB	5420	SBB	5491	SBB
100	5276	SBB	5633	SBB	5752	SBB	6056	SBB	6065	SBB	6093	SBB	6243	SBT	6113	SBB	6211	SBT	6204	SBB

Table 10
Total emissions (kg CO2e) for expected value of blocks = 20 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	358	SBB	381	SBB	396	SBB	399	SBB	417	SBB	426	SBB	416	SBB	431	SBB	423	SBB	425	SBB
20	765	SBB	797	SBB	852	SBB	848	SBB	886	SBB	906	SBB	881	SBB	897	SBB	886	SBB	904	SBB
30	1202	SBB	1302	SBB	1350	SBB	1420	SBB	1400	SBB	1370	SBB	1389	SBB	1436	SBB	1435	SBB	1422	SBB
40	1688	SBB	1827	SBB	1895	SBB	1986	SBB	1989	SBB	2031	SBB	2020	SBB	2042	SBB	2006	SBB	1993	SBB
50	2186	SBB	2405	SBB	2467	SBB	2519	SBB	2615	SBB	2618	SBB	2569	SBB	2631	SBB	2635	SBB	2622	SBB
60	2830	SBB	2954	SBB	3193	SBB	3221	SBB	3278	SBB	3223	SBB	3246	SBB	3243	SBB	3360	SBB	3327	SBB
70	3443	SBB	3579	SBB	3766	SBB	3835	SBB	3998	SBB	3976	SBB	4014	SBB	3949	SBB	3970	SBB	4054	SBB
80	4154	SBB	4296	SBB	4480	SBB	4599	SBB	4551	SBB	4581	SBB	4756	SBB	4861	SBB	4744	SBB	4696	SBB
90	4778	SBB	4954	SBB	5277	SBB	5335	SBB	5321	SBB	5313	SBB	5502	SBB	5545	SBB	5421	SBB	5391	SBB
100	5547	SBB	5678	SBB	5968	SBB	6121	SBB	6416	SBB	6194	SBB	6216	SBB	6350	SBB	6258	SBB	6380	SBB

Table 11
Total emissions (kg CO2e) for expected value of blocks = 25 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	391	SBB	434	SBB	439	SBB	449	SBB	455	SBB	458	SBB	465	SBB	467	SBB	485	SBB	479	SBB
20	822	SBB	915	SBB	929	SBB	949	SBB	996	SBB	961	SBB	963	SBB	951	SBB	1004	SBB	992	SBB
30	1353	SBB	1403	SBB	1450	SBB	1571	SBB	1544	SBB	1623	SBB	1553	SBB	1535	SBB	1585	SBB	1587	SBB
40	1895	SBB	1943	SBB	2055	SBB	2100	SBB	2214	SBB	2209	SBB	2241	SBB	2206	SBB	2213	SBB	2258	SBB
50	2470	SBB	2632	SBB	2704	SBB	2817	SBB	2823	SBB	2852	SBB	2786	SBB	2851	SBB	2902	SBB	2870	SBB
60	3165	SBB	3304	SBB	3429	SBB	3519	SBB	3563	SBB	3652	SBB	3632	SBB	3527	SBB	3598	SBB	3704	SBB
70	3891	SBB	3978	SBB	4101	SBB	4150	SBB	4353	SBB	4313	SBB	4326	SBB	4431	SBB	4454	SBB	4404	SBB
80	4628	SBB	4786	SBB	4915	SBB	4948	SBB	5002	SBB	5236	SBB	5025	SBB	5340	SBB	5105	SBB	5159	SBB
90	5476	SBB	5557	SBB	5768	SBB	5765	SBB	5884	SBB	6012	SBB	6033	SBB	6091	SBB	6051	SBB	6023	SBB
100	6367	SBB	6341	SBB	6601	SBB	6726	SBB	6721	SBB	6807	SBB	6849	SBB	6992	SBB	6862	SBB	6757	SBB

Table 12
Total emissions (kg CO2e) for expected value of blocks = 30 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	409	SBB	478	SBB	482	SBB	465	SBB	488	SBB	487	SBB	515	SBB	514	SBB	513	SBB	502	SBB
20	906	SBB	933	SBB	1038	SBB	1029	SBB	1048	SBB	1056	SBB	1080	SBB	1087	SBB	1052	SBB	1099	SBB
30	1413	SBB	1529	SBB	1602	SBB	1651	SBB	1687	SBB	1665	SBB	1684	SBB	1683	SBB	1661	SBB	1700	SBB
40	2053	SBB	2232	SBB	2254	SBB	2257	SBB	2381	SBB	2339	SBB	2323	SBB	2360	SBB	2344	SBB	2346	SBB
50	2710	SBB	2911	SBB	2869	SBB	2996	SBB	2996	SBB	3052	SBB	3171	SBB	3035	SBB	3162	SBB	3129	SBB
60	3464	SBB	3591	SBB	3665	SBB	3786	SBB	3827	SBB	3876	SBB	3782	SBB	3919	SBB	3894	SBB	3832	SBB
70	4258	SBB	4197	SBB	4521	SBB	4529	SBB	4638	SBB	4641	SBB	4668	SBB	4817	SBB	4637	SBB	4704	SBB
80	5158	SBB	5120	SBB	5378	SBB	5424	SBB	5412	SBB	5321	SBB	5431	SBB	5580	SBB	5465	SBB	5566	SBB
90	6087	SBB	5988	SBB	6260	SBB	6588	SBB	6290	SBB	6358	SBB	6590	SBB	6503	SBB	6430	SBB	6401	SBB
100	7104	SBB	6950	SBB	6999	SBB	7241	SBB	7401	SBB	6988	SBB	7301	SBB	7205	SBB	7158	SBB	7362	SBB

Table 13
Total emissions (kg CO2e) for expected value of blocks = 10 and two sequential periods (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	309	PPS	314	PPS	319	PPS	323	PPS	328	PPS	325	PPS	331	PPS	332	PPS	328	PPS	335	PPS
20	612	SBB	622	SBB	636	SBB	643	SBB	652	SBB	654	SBB	654	SBB	654	SBB	659	SBB	655	SBB
30	917	SBB	933	SBB	945	SBB	954	SBB	958	SBB	962	SBB	963	SBB	972	SBB	974	SBB	970	SBB
40	1245	SBB	1241	SBB	1240	SBB	1257	SBB	1260	SBB	1264	SBB	1265	SBB	1280	SBB	1288	SBB	1270	SBB
50	1595	SBB	1548	SBB	1557	SBB	1554	SBB	1570	SBB	1588	SBB	1570	SBB	1586	SBB	1577	SBB	1583	SBB
60	1970	SBB	1874	SBB	1872	SBB	1879	SBB	1870	SBB	1869	SBB	1886	SBB	1894	SBB	1869	SBB	1892	SBB
70	2348	SBB	2212	SBB	2190	SBB	2189	SBB	2181	SBB	2193	SBB	2187	SBB	2196	SBB	2181	SBB	2185	SBB
80	2777	SBB	2558	SBB	2515	SBB	2516	SBB	2501	SBB	2506	SBB	2489	SBB	2501	SBB	2499	SBB	2495	SBB
90	3193	SBB	2928	SBB	2861	SBB	2838	SBB	2823	SBB	2801	SBB	2810	SBB	2802	SBB	2801	SBB	2785	SBB
100	3661	SBB	3303	SBB	3202	SBB	3178	SBB	3135	SBB	3136	SBB	3120	SBB	3103	SBB	3123	SBB	3101	SBB

Table 14
Total emissions (kg CO2e) for expected value of blocks = 20 and two sequential periods (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	404	PPS	411	PPS	415	PPS	423	PPS	423	PPS	424	PPS	431	PPS	425	PPS	424	PPS	425	PPS
20	773	SBB	830	SBB	852	PPS	863	PPS	866	PPS	868	PPS	876	PPS	883	PPS	882	PPS	883	PPS
30	1140	SBB	1193	SBB	1222	SBB	1249	SBB	1261	SBB	1261	SBB	1271	SBB	1281	SBB	1266	SBB	1267	SBB
40	1524	SBB	1556	SBB	1585	SBB	1636	SBB	1639	SBB	1644	SBB	1638	SBB	1654	SBB	1650	SBB	1653	SBB
50	1947	SBB	1920	SBB	1955	SBB	1998	SBB	2011	SBB	2010	SBB	2020	SBB	2012	SBB	2018	SBB	2019	SBB
60	2416	SBB	2327	SBB	2345	SBB	2368	SBB	2379	SBB	2372	SBB	2370	SBB	2364	SBB	2383	SBB	2384	SBB
70	2847	SBB	2717	SBB	2703	SBB	2732	SBB	2730	SBB	2733	SBB	2749	SBB	2739	SBB	2727	SBB	2740	SBB
80	3345	SBB	3136	SBB	3091	SBB	3114	SBB	3111	SBB	3098	SBB	3111	SBB	3106	SBB	3100	SBB	3091	SBB
90	3858	SBB	3530	SBB	3504	SBB	3488	SBB	3457	SBB	3468	SBB	3475	SBB	3451	SBB	3482	SBB	3442	SBB
100	4445	SBB	3984	SBB	3902	SBB	3887	SBB	3855	SBB	3860	SBB	3818	SBB	3815	SBB	3793	SBB	3810	SBB

Table 15
Total emissions (kg CO2e) for expected value of blocks = 30 and two sequential periods (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	517	PPS	521	PPS	532	PPS	530	PPS	541	PPS	538	PPS	542	PPS	548	PPS	541	PPS	551	PPS
20	980	SBB	1055	SBB	1079	SBB	1107	SBB	1104	SBB	1106	PPS	1123	SBB	1119	PPS	1129	SBB	1127	PPS
30	1473	SBB	1518	SBB	1561	SBB	1579	SBB	1601	SBB	1611	SBB	1610	SBB	1612	SBB	1613	SBB	1616	SBB
40	1973	SBB	1997	SBB	2016	SBB	2052	SBB	2069	SBB	2076	SBB	2085	SBB	2093	SBB	2080	SBB	2092	SBB
50	2540	SBB	2484	SBB	2489	SBB	2494	SBB	2530	SBB	2548	SBB	2544	SBB	2549	SBB	2539	SBB	2541	SBB
60	3110	SBB	2943	SBB	2959	SBB	2998	SBB	2981	SBB	2997	SBB	3011	SBB	3004	SBB	3010	SBB	2999	SBB
70	3762	SBB	3497	SBB	3454	SBB	3475	SBB	3483	SBB	3484	SBB	3440	SBB	3467	SBB	3458	SBB	3447	SBB
80	4452	SBB	4041	SBB	3979	SBB	3938	SBB	3951	SBB	3940	SBB	3930	SBB	3918	SBB	3901	SBB	3885	SBB
90	5227	SBB	4639	SBB	4479	SBB	4475	SBB	4437	SBB	4408	SBB	4396	SBB	4367	SBB	4357	SBB	4336	SBB
100	5930	SBB	5213	SBB	5057	SBB	5006	SBB	4913	SBB	4888	SBB	4863	SBB	4828	SBB	4811	SBB	4796	SBB

Table 16
Average number of pulled back railcars for expected value of blocks = 5 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	409	SBB	425	SBB	431	SBB	440	SBB	458	SBB	446	SBB	444	SBB	450	SBB	468	SBB	464	SBB
20	934	SBB	1011	SBB	1073	SBB	1121	SBB	1077	SBB	1154	SBB	1142	SBB	1108	SBB	1152	SBB	1158	SBB
30	1458	SBB	1684	SBB	1743	SBT	1753	SBT	1746	SBT	1752	SBT	1762	SBT	1741	SBT	1747	SBT	1750	SBT
40	2030	SBB	2339	SBT	2329	SBT	2325	SBT	2329	SBT	2330	SBT	2319	SBT	2320	SBT	2334	SBT	2327	SBT
50	2595	SBB	2916	SBT	2922	SBT	2916	SBT	2926	SBT	2927	SBT	2917	SBT	2912	SBT	2922	SBT	2921	SBT
60	3201	SBB	3499	SBT	3496	SBT	3491	SBT	3502	SBT	3507	SBT	3500	SBT	3493	SBT	3504	SBT	3499	SBT
70	3807	SBB	4080	SBT	4086	SBT	4081	SBT	4086	SBT	4090	SBT	4082	SBT	4084	SBT	4082	SBT	4065	SBT
80	4470	SBB	4662	SBT	4665	SBT	4678	SBT	4656	SBT	4663	SBT	4660	SBT	4655	SBT	4662	SBT	4667	SBT
90	5017	SBB	5242	SBT	5252	SBT	5282	SBT	5228	SBT	5253	SBT	5258	SBT	5259	SBT	5251	SBT	5255	SBT
100	5619	SBB	5829	SBT	5840	SBT	5810	SBT	5838	SBT	5844	SBT	5835	SBT	5835	SBT	5835	SBT	5828	SBT

Table 17
Average number of pulled back railcars for expected value of blocks = 10 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	386	SBB	444	SBB	473	SBB	474	SBB	480	SBB	483	SBB	483	SBB	500	SBB	477	SBB	485	SBB
20	879	SBB	1033	SBB	1137	SBB	1143	SBT	1133	SBB	1141	SBT	1150	SBT	1147	SBT	1140	SBT	1150	SBT
30	1444	SBB	1721	SBT	1719	SBT	1728	SBT	1735	SBT	1731	SBT	1717	SBT	1735	SBT	1734	SBT	1728	SBT
40	2005	SBB	2294	SBT	2300	SBT	2298	SBT	2308	SBT	2291	SBT	2304	SBT	2303	SBT	2302	SBT	2305	SBT
50	2608	SBB	2883	SBT	2864	SBT	2884	SBT	2869	SBT	2887	SBT	2868	SBT	2859	SBT	2866	SBT	2864	SBT
60	3207	SBB	3462	SBT	3449	SBT	3453	SBT	3456	SBT	3453	SBT	3457	SBT	3451	SBT	3449	SBT	3431	SBT
70	3767	SBB	4037	SBT	4022	SBT	4021	SBT	4020	SBT	4026	SBT	4025	SBT	4023	SBT	4031	SBT	4014	SBT
80	4446	SBB	4600	SBT	4603	SBT	4586	SBT	4614	SBT	4595	SBT	4598	SBT	4588	SBT	4599	SBT	4604	SBT
90	5123	SBB	5187	SBT	5167	SBT	5205	SBT	5162	SBT	5162	SBT	5164	SBT	5166	SBT	5171	SBT	5178	SBT
100	5743	SBB	5752	SBT	5752	SBT	5741	SBT	5746	SBT	5766	SBT	5757	SBT	5740	SBT	5753	SBT	5757	SBT

Table 18
Average number of pulled back railcarss for expected value of blocks = 15 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	401	SBB	450	SBB	464	SBB	481	SBB	491	SBB	488	SBB	487	SBB	488	SBB	492	SBB	484	SBB
20	868	SBB	1021	SBB	1108	SBB	1117	SBB	1156	SBB	1201	SBT	1133	SBB	1191	SBB	1192	SBT	1205	SBT
30	1423	SBB	1652	SBB	1790	SBT	1793	SBT	1793	SBT	1782	SBT	1793	SBT	1795	SBT	1795	SBT	1796	SBT
40	1925	SBB	2379	SBT	2394	SBT	2390	SBT	2392	SBT	2384	SBT	2399	SBT	2385	SBT	2385	SBT	2405	SBT
50	2594	SBB	2983	SBT	2990	SBT	2992	SBT	2989	SBT	2980	SBT	2992	SBT	2989	SBT	2994	SBT	2986	SBT
60	3071	SBB	3598	SBT	3587	SBT	3586	SBT	3573	SBT	3579	SBT	3596	SBT	3581	SBT	3584	SBT	3589	SBT
70	3698	SBB	4183	SBT	4184	SBT	4180	SBT	4190	SBT	4178	SBT	4187	SBT	4179	SBT	4186	SBT	4180	SBT
80	4288	SBB	4779	SBT	4776	SBT	4788	SBT	4773	SBT	4789	SBT	4778	SBT	4781	SBT	4769	SBT	4783	SBT
90	4864	SBB	5368	SBT	5386	SBT	5382	SBT	5371	SBT	5370	SBT	5378	SBT	5368	SBT	5374	SBT	5370	SBT
100	5569	SBB	5995	SBT	5994	SBT	5984	SBT	5997	SBT	5999	SBT	5971	SBT	5985	SBT	5967	SBT	5974	SBT

Table 19
Average number of pulled back railcars for expected value of blocks = 20 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	421	SBB	462	SBB	485	SBB	488	SBB	511	SBB	532	SBB	513	SBB	535	SBB	521	SBB	523	SBB
20	951	SBB	1047	SBB	1152	SBB	1151	SBB	1220	SBB	1258	SBB	1208	SBB	1239	SBB	1220	SBB	1250	SBB
30	1476	SBB	1761	SBB	1887	SBB	2004	SBT	1987	SBT	1939	SBB	1981	SBB	1991	SBT	1984	SBT	1980	SBT
40	2017	SBB	2468	SBB	2643	SBT	2631	SBT	2656	SBT	2638	SBT	2639	SBT	2656	SBT	2642	SBT	2648	SBT
50	2519	SBB	3227	SBB	3292	SBT	3295	SBT	3307	SBT	3308	SBT	3300	SBT	3288	SBT	3311	SBT	3315	SBT
60	3246	SBB	3865	SBB	3937	SBT	3961	SBT	3960	SBT	3954	SBT	3971	SBT	3956	SBT	3969	SBT	3962	SBT
70	3778	SBB	4617	SBT	4622	SBT	4624	SBT	4629	SBT	4642	SBT	4627	SBT	4615	SBT	4611	SBT	4635	SBT
80	4486	SBB	5297	SBT	5288	SBT	5273	SBT	5278	SBT	5270	SBT	5278	SBT	5276	SBT	5281	SBT	5285	SBT
90	4970	SBB	5949	SBT	5946	SBT	5960	SBT	5950	SBT	5930	SBT	5956	SBT	5951	SBT	5941	SBT	5951	SBT
100	5642	SBB	6599	SBT	6602	SBT	6620	SBT	6629	SBT	6586	SBT	6590	SBT	6615	SBT	6612	SBT	6614	SBT

Table 20
Average number of pulled back railcars for expected value of blocks = 25 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	454	SBB	526	SBB	539	SBB	550	SBB	559	SBB	561	SBB	572	SBB	576	SBB	600	SBB	594	SBB
20	991	SBB	1206	SBB	1246	SBB	1285	SBB	1375	SBB	1311	SBB	1316	SBB	1291	SBB	1388	SBB	1363	SBB
30	1625	SBB	1852	SBB	1976	SBB	2224	SBB	2182	SBB	2283	SBT	2208	SBB	2178	SBB	2264	SBT	2274	SBT
40	2196	SBB	2520	SBB	2815	SBB	2929	SBB	3023	SBT	3027	SBT	3022	SBT	3011	SBT	3027	SBT	3031	SBT
50	2725	SBB	3408	SBB	3664	SBB	3782	SBT	3776	SBT	3776	SBT	3771	SBT	3768	SBT	3780	SBT	3778	SBT
60	3442	SBB	4222	SBB	4548	SBT	4533	SBT	4518	SBT	4530	SBT	4523	SBT	4531	SBT	4538	SBT	4529	SBT
70	4101	SBB	4980	SBB	5284	SBT	5273	SBT	5293	SBT	5270	SBT	5263	SBT	5301	SBT	5270	SBT	5320	SBT
80	4640	SBB	5915	SBB	6052	SBT	6060	SBT	6019	SBT	6069	SBT	6052	SBT	5999	SBT	6041	SBT	6034	SBT
90	5364	SBB	6689	SBB	6798	SBT	6783	SBT	6782	SBT	6804	SBT	6772	SBT	6805	SBT	6777	SBT	6774	SBT
100	6111	SBB	7492	SBB	7559	SBT	7544	SBT	7532	SBT	7540	SBT	7530	SBT	7543	SBT	7561	SBT	7561	SBT

Table 21
Average number of pulled back railcars for expected value of blocks = 30 (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	469	SBB	592	SBB	595	SBB	573	SBB	608	SBB	601	SBB	645	SBB	641	SBB	644	SBB	621	SBB
20	1080	SBB	1200	SBB	1407	SBB	1404	SBB	1437	SBB	1451	SBB	1494	SBB	1509	SBB	1451	SBB	1534	SBB
30	1624	SBB	2000	SBB	2197	SBB	2308	SBB	2389	SBB	2359	SBB	2399	SBB	2397	SBB	2358	SBB	2430	SBB
40	2307	SBB	2944	SBB	3066	SBB	3116	SBB	3295	SBT	3308	SBT	3295	SBB	3299	SBT	3296	SBT	3291	SBT
50	2940	SBB	3759	SBB	3822	SBB	4121	SBT	4105	SBT	4118	SBT	4128	SBT	4124	SBT	4123	SBT	4137	SBT
60	3622	SBB	4517	SBB	4857	SBB	4954	SBT	4930	SBT	4936	SBT	4935	SBT	4954	SBT	4941	SBT	4938	SBT
70	4345	SBB	5058	SBB	5762	SBT	5765	SBT	5758	SBT	5764	SBT	5787	SBT	5753	SBT	5772	SBT	5767	SBT
80	5086	SBB	6131	SBB	6587	SBT	6600	SBT	6602	SBT	6588	SBT	6580	SBT	6584	SBT	6609	SBT	6578	SBT
90	5813	SBB	7019	SBB	7413	SBT	7401	SBT	7417	SBT	7428	SBT	7406	SBT	7417	SBT	7410	SBT	7424	SBT
100	6590	SBB	8009	SBB	8238	SBT	8273	SBT	8224	SBT	8239	SBT	8232	SBT	8235	SBT	8233	SBT	8243	SBT

Table 22
Average number of pulled back railcars for expected value of blocks = 10 and two sequential periods (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	296	SBB	301	SBB	309	SBB	311	SBB	315	SBB	310	SBB	315	SBB	317	SBB	318	SBB	320	SBB
20	610	SBB	625	SBB	642	SBB	660	SBB	662	SBB	670	SBB	670	SBB	670	SBB	676	SBB	673	SBB
30	925	SBB	968	SBB	994	SBB	1014	SBB	1026	SBB	1036	SBB	1047	SBB	1058	SBB	1057	SBB	1054	SBB
40	1236	SBB	1310	SBB	1328	SBB	1372	SBB	1390	SBB	1410	SBB	1418	SBB	1444	SBB	1451	SBB	1430	SBB
50	1543	SBB	1628	SBB	1704	SBB	1726	SBB	1765	SBB	1808	SBB	1796	SBB	1833	SBB	1816	SBB	1832	SBB
60	1873	SBB	1957	SBB	2047	SBB	2114	SBB	2134	SBB	2152	SBB	2192	SBB	2212	SBB	2195	SBB	2231	SBB
70	2174	SBB	2291	SBB	2402	SBB	2468	SBB	2506	SBB	2552	SBB	2565	SBB	2602	SBB	2588	SBB	2600	SBB
80	2477	SBB	2632	SBB	2755	SBB	2840	SBB	2883	SBB	2938	SBB	2934	SBB	2974	SBB	2994	SBB	2995	SBB
90	2804	SBB	2981	SBB	3096	SBB	3193	SBB	3258	SBB	3292	SBB	3338	SBB	3350	SBB	3363	SBB	3364	SBB
100	3084	SBB	3303	SBB	3454	SBB	3572	SBB	3601	SBB	3678	SBB	3708	SBB	3717	SBB	3770	SBB	3759	SBB

Table 23
Average number of pulled back railcars for expected value of blocks = 20 and two sequential periods (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	351	SBB	359	SBB	359	SBB	367	SBB	368	SBB	370	SBB	375	SBB	372	SBB	369	SBB	372	SBB
20	705	SBB	744	SBB	769	SBB	782	SBB	787	SBB	794	SBB	797	SBB	811	SBB	810	SBB	809	SBB
30	1070	SBB	1141	SBB	1180	SBB	1210	SBB	1231	SBB	1236	SBB	1246	SBB	1264	SBB	1247	SBB	1248	SBB
40	1444	SBB	1532	SBB	1596	SBB	1664	SBB	1678	SBB	1701	SBB	1702	SBB	1726	SBB	1724	SBB	1733	SBB
50	1807	SBB	1920	SBB	2019	SBB	2091	SBB	2132	SBB	2159	SBB	2172	SBB	2182	SBB	2196	SBB	2194	SBB
60	2184	SBB	2345	SBB	2448	SBB	2531	SBB	2587	SBB	2602	SBB	2622	SBB	2633	SBB	2657	SBB	2670	SBB
70	2536	SBB	2709	SBB	2853	SBB	2961	SBB	3007	SBB	3065	SBB	3107	SBB	3111	SBB	3111	SBB	3140	SBB
80	2887	SBB	3086	SBB	3266	SBB	3408	SBB	3468	SBB	3506	SBB	3568	SBB	3579	SBB	3589	SBB	3589	SBB
90	3249	SBB	3460	SBB	3693	SBB	3813	SBB	3878	SBB	3967	SBB	4019	SBB	4015	SBB	4085	SBB	4064	SBB
100	3606	SBB	3887	SBB	4079	SBB	4272	SBB	4353	SBB	4442	SBB	4445	SBB	4474	SBB	4489	SBB	4531	SBB

Table 24
Average number of pulled back railcars for expected value of blocks = 30 and two sequential periods (ot = number of outgoing trains, it = number of incoming trains).

ot\it	10		20		30		40		50		60		70		80		90		100	
10	436	SBB	446	SBB	458	SBB	459	SBB	469	SBB	465	SBB	467	SBB	475	SBB	468	SBB	479	SBB
20	881	SBB	945	SBB	970	SBB	998	SBB	998	SBB	1007	SBB	1024	SBB	1020	SBB	1027	SBB	1028	SBB
30	1349	SBB	1441	SBB	1497	SBB	1543	SBB	1571	SBB	1588	SBB	1591	SBB	1601	SBB	1602	SBB	1609	SBB
40	1800	SBB	1952	SBB	2016	SBB	2084	SBB	2134	SBB	2151	SBB	2181	SBB	2196	SBB	2192	SBB	2206	SBB
50	2270	SBB	2444	SBB	2540	SBB	2625	SBB	2689	SBB	2742	SBB	2768	SBB	2782	SBB	2781	SBB	2802	SBB
60	2693	SBB	2898	SBB	3044	SBB	3199	SBB	3239	SBB	3318	SBB	3357	SBB	3382	SBB	3401	SBB	3392	SBB
70	3164	SBB	3411	SBB	3595	SBB	3750	SBB	3845	SBB	3917	SBB	3907	SBB	3960	SBB	3982	SBB	3983	SBB
80	3606	SBB	3911	SBB	4134	SBB	4276	SBB	4407	SBB	4479	SBB	4521	SBB	4544	SBB	4556	SBB	4566	SBB
90	4131	SBB	4387	SBB	4652	SBB	4890	SBB	4981	SBB	5064	SBB	5094	SBB	5126	SBB	5146	SBB	5134	SBB
100	4519	SBB	4913	SBB	5212	SBB	5458	SBB	5525	SBB	5619	SBB	5654	SBB	5684	SBB	5714	SBB	5746	SBB

previous shunted tracks $k' \leqslant k$ in period t results in the set of blocks w of the sequenced blocks set j which are actually shunted on track k.

If blocks of each shunted and sequenced blocks set are combined, the result is the set of blocks of train $r \in \mathscr{R}$ which are shunted from classification track k to other tracks in period t and can be expressed by $W'^{TS/GS,r}_{t,k} = \bigcup_{j=1}^{\bar{j}_k^{TS/GS,r}} W'^{TS/GS,r}_{t,k,j}$. Finally, the sorting performance for TS and GS is derived as

$$SP_t^{TS/GS}\left(\mathscr{W}_t, \mathscr{R}_t\right) = \bigcup_{k=1,\dots,\bar{g}_t-1} \sum_{r \in \mathscr{R}_t} \left(\sum_{w \in W'^{TS/GS,r}_{t,k}} v_{w,r} \right) \tag{20}$$

In each period t sorting performances are determined for each track $k \leqslant \bar{g}_t - 1$ by summing up railcars of pulled back blocks $w \in W'^{TS/GS,r}_{t,k}$ for each train $r \in \mathscr{R}_t$. These sorting performances correspond to the total number of shunted railcars on each track k.

2.2.5. Rolling horizon approach for parallel pullbacks

To derive the sorting performance for PPS in a rolling horizon setting, basic assumptions have to be made. If blocks of not constructable trains are in the classification tracks these blocks are rehumped to the same classification track. If there are no constructable trains in the marshalling yard, no sorting step is carried out. Let $\bar{k}$ be the number of available classification tracks for PPS. Each outgoing train $r \in \mathscr{R}$ is numbered from 1 to n_r, where n_r denotes its number of blocks. d_r marks the number of sets for train $r \in \mathscr{R}$. $s_{\bar{k}}^r := \lceil log_{\bar{k}} d_r \rceil$ denotes the number of sorting steps to construct train $r \in \mathscr{R}$ with $\bar{k}$ available classification tracks. Let $B^r[j]$ $(j = 1,\dots,d_r)$ be the initial assignment of blocks of train $r \in \mathscr{R}$ to batches. The set of batches of train $r \in \mathscr{R}$ in sorting step pss on track k can be expressed by

$$BU^r\left(pss, k, d_r\right) = \bigcup_{i=0}^{lim_1(pss,k,d_r)} \bigcup_{j=1}^{lim_2(pss,k,i,d_r)} B^r\left[j + \left(k-1\right)\bar{k}^{pss-1} + \bar{k}^{pss} i\right] \tag{21}$$

$$lim_1\left(pss, k, d_r\right) = \left\lceil \frac{d_r - (k-1)\bar{k}^{pss-1}}{\bar{k}^{pss}} \right\rceil \tag{22}$$

$$lim_2(pss, k, i, d_r) = \min\left(\bar{k}^{pss-1}, d_r - (k-1)\bar{k}^{pss-1} - \bar{k}^{pss} i\right) \tag{23}$$

The main idea is to derive sets of blocks by initial sets $B^r[j]$. For each sorting step pss and on each classification track k different initial sets have to be chosen. Therefore, consider the three terms of the square brackets: 'j' is the amount of consecutively chosen initial sets, i.e. either $\bar{k}^{pss-1}$ initial sets are chosen or if no initial sets are available, less classification tracks are chosen, see $lim_2(pss,k,i,d_r)$. Term $(k-1)\bar{k}^{pss-1}$ shifts the initial set chosen first for each classification track, e.g. on classification track $k = 1$ the initial set chosen first is $B^r[1]$, on classification track $k = 2$ the second chosen set is $B^r[2]$, and so on. Term $\bar{k}^{pss} i$ shifts the initial sets on a classification track up to $lim_1(pss, k, d_r)$, e.g. in a marshalling yard with $\bar{k} = 3$ classificiaton tracks in total, the selected initial sets are $B^r[1], B^r[4], B^r[7], \dots$ on classification track $k = 1$ in sorting step $pss = 1$.

Let $\bar{t}_{ko}^r$ be the period when all blocks of train $r \in \mathscr{R}$ arrived in the marshalling yard, i.e. train $r \in \mathscr{R}$ is constructable. If $\bar{g}_t$ describes the termination criterion of PPS in period t the number of conducted sorting steps before period t can be expressed by $\bar{y}_t^r = \sum_{t'=\bar{t}_{ko}^r}^{t-1} (\bar{g}_{t'} - 1)$. Set $W_{t,0}^{PPS,r}$ describes incoming blocks of train $r \in \mathscr{R}_t$ in period $t - 1$. Let $W'^{PPS,r}_{t,k,pss}$ be the set of shunted blocks of train $r \in \mathscr{R}_t$ in period t on track k for sorting step pss which can be expressed by

$$W'^{PPS,r}_{t,k,pss} = \begin{cases} BU^r\left(1, k, d_r\right) \cap \bigcup_{t'=1}^{t} W^{PPS,r}_{t',0} & \text{for } \bar{t}_{ko}^r > t \\ BU^r\left(\bar{y}_t^r + pss, k, d_r\right) & \text{for } \bar{t}_{ko}^r \leqslant t \wedge \bar{y}_t^r + pss \leqslant s_{\bar{k}}^r \\ \varnothing & \text{for } \bar{t}_{ko}^r \leqslant t \wedge \bar{y}_t^r + pss > s_{\bar{k}}^r \end{cases}. \tag{24}$$

If train $r \in \mathscr{R}_t$ is not constructable in period t, i.e. $\bar{t}_{ko}^r > t$, blocks of train $r \in \mathscr{R}_t$ remain or can be rehumped on the track after initial humping. $BU^r(1, k, d_r)$ denotes the set of blocks which are theoretical on track k after sorting step $pss = 1$. $\bigcup_{t'=1}^{t} W^{PPS,r}_{t',0}$ reveals the blocks in the marshalling yard of train r up to period t. The intersection of both sets denotes the actual set of blocks of train r on track k. If $\bar{t}_{ko}^r \leqslant t$ holds, two cases may arise: If $\bar{y}_t^r + pss \leqslant s_{\bar{k}}^r$, i.e. the number of previous conducted sorting steps plus the actual sorting step of period t is less or equal to the number of necessary sorting steps of train $r \in \mathscr{R}_t$, blocks of train $r \in \mathscr{R}_t$ have to be shunted. Otherwise no more sorting steps of train r are necessary and the set of shunted blocks is empty. Finally, the sorting performance of PPS can be expressed by

$$SP_t^{PPS}\left(\mathscr{W}_t, \mathscr{R}_t\right) = \bigcup_{pss=1}^{\bar{g}_t-1} \bigcup_{k=1}^{\bar{k}} \left\{ \sum_{r \in \mathscr{R}_t} \left(\sum_{w \in W'^{PPS,r}_{t,k,pss}} v_{w,r} \right) \right\}. \tag{25}$$

Sorting performance values are determined for each sorting step pss and each classification track k in period t. Each value consists of railcars of shunted blocks $W'^{PPS,r}_{t,k,pss}$ of train $r \in \mathscr{R}_t$.

3. Emission model for shunting operations

The chosen emission model for the simulation in Section 4 is presented in this section. Because there is no emission model for marshalling yards, a model of the related field rail transportation is applied. An overview of models in rail transportation (microscopic/macroscopic/mesoscopic) can be found in Heinold (2020). In this paper the mesoscopic emission model of Kirschstein and Meisel (2015) is applied. The main idea of the paper is to overcome the four resistances rolling P^{roll}, air drag P^{air}, ascent P^{grade} and acceleration P^{inert}. The approximation of a train's total energy demand is calculated as

$$\bar{E}\left(d, m, \bar{v}, \bar{i}, n^{acc}\right) = \frac{d}{\bar{v}}\left(P^{roll}(\bar{v}, m) + P^{air}(\bar{v}) + P^{grade}(\bar{v}, \bar{i}, m)\right) + n^{acc} \cdot \hat{E}^{inert}\left(v, m\right). \tag{26}$$

where the three resistances rolling P^{roll}, air drag P^{air} and ascent P^{grade} can be calculated with the average speed of the train $\bar{v}$ and the mass m of the train. However, the energy to overcome acceleration resistance must be approximated by $\hat{E}^{inert}$ with speed v and mass m while parameter n^{acc} represents the average number of acceleration processes per kilometer by the train.

If $\in$ denotes the energy transformation efficiency of the locomotive, p the fuel energy coefficient of Diesel and k the GHG emission coefficient of Diesel, the GHG emissions of a diesel train can be calculated with (26) by

$$GHG\left(d, m, \bar{v}, \bar{i}, n^{acc}\right) = \frac{\bar{E}(d, m, \bar{v}, \bar{i}, n^{acc})}{\in} \cdot p \cdot k \tag{27}$$

Generalized marshalling operations consist of 'inbound train processing', 'shunting operations' and 'outbound train processing'. Whenever an incoming train arrives in the yard railcars are decoupled and the locomotive is detached. Afterwards, shunting operations are run through a shunting locomotive which is followed by the coupling of railcars and the locomotive. Because incoming and outgoing full trains are only moved over small distances these operations are neglected. Therefore, the main focus is on the shunting operations.

Shunting operations can be distinguished into three suboperations, i.e. humping of the railcars, repositioning of the shunting locomotive and pulling back of railcars. First, the shunting locomotive pushes the railcars from the receiving tracks over the hump into the receiving area. Another shunting operation is the moving of the shunting locomotive from the receiving tracks to the classification tracks. After the arrival at the classification tracks, the shunting locomotive pulls back the railcars from the classification tracks into the receiving tracks. The layout of the marshalling yard determines the distances covered by the railcars and locomotives in each step of the shunting process. Reposition distance of the shunting locomotive from the receiving tracks into the classification tracks is denoted by d^{rp} and from the classification tracks into the receiving tracks by d^{pb}.

Beyond travelling distances, some further parameters have to be determined to apply (27). It is assumed that each railcar has a fixed gross weight m^{RC} and a fixed length l^{RC}. Because total mass includes also the mass of the shunting locomotive, the locomotives weight is denoted as m^{loc}. In (27) height $\bar{i}$ is included for detailed calculation. In marshalling yards $\bar{i}$ represents the height of the hump for the humping process and is set to $\bar{i} = 0$ for the remaining shunting operations. Also the speed $\bar{\nu}$ is assumed to be fixed and $n^{acc} = 1$. Depending on the selected sorting strategy the number of pullbacks n_t^{pb} in period t and the number of incoming trains n_t^{it} in period t influence the GHG emissions. If s_i^{it} denotes the number of railcars in the incoming train i and s_j^{pb} the number of pulled back railcars in step j the GHG emissions in period t can be calculated by

$$GHG_t(s^{it}, s^{pb}) = n_t^{pb} \cdot GHG(d^{rp}, m^{loc}, \bar{\nu}, 0, 1) + \sum_{j=1}^{n_t^{pb}} GHG(d^{pb}, m^{loc} + s_j^{pb} \cdot m^{RC}, \bar{\nu}, 0, 1) + \sum_{i=1}^{n_t^{it}} GHG\left(s_i^{it} \cdot l^{RC}, m^{loc} + s_i^{it} \cdot m^{RC}, \bar{\nu}, \frac{h}{s_i^{it} \cdot l^{RC}}, 1\right) \tag{28}$$

4. Simulation experiments

The rolling horizon model is evaluated in a simulation study. For this purpose, an exemplary marshalling yard is assumed inspired by a real-world example. The corresponding technical parameters for layout, railcars and locomotives are described in Subsection 4.1. For the remaining parameters (like number of periods or number of outgoing trains) preliminary investigations are conducted to determine reasonable intervals affecting greenhouse gas emissions. The results show that three of five sorting strategies are preferred w.r.t. minimal total emissions, see Subsection 4.2.

4.1. Experimental design

The technical parameters required for the simulation study concern shunting locomotives, railcars and the layout of the yard. In the following, the layout of the marshalling yard in Halle(Saale) is used. to determine distance parameters d^{rp} and d^{pb}. The reposition distance, i.e. the distance from receiving tracks to classification tracks, is set to $d^{rp} = 1$ km. Whenever a shunting locomotive pulls back railcars, the pull back distance is $d^{pb} = 1.5$ km. The length of the classification tracks is 1 km. In contrast to reality, the number of classification tracks is unlimited because the above mentioned sorting strategies (except PPS) cannot be applied when the number of classification tracks is limited (the case of a limited number of classification tracks should be studied in further investigations). The average speed of the shunting locomotive is assumed to be 8 km/h. That is lower than the maximum speed of 25 km/h, but shunting locomotives usually drive slower during shunting due to safety and operational reasons. In the following experiments, the termination criterion $\bar{g}_t$ for each period is the time when all constructable trains of a period are left in the marshalling yard.

The data generation for the simulation comprises a variety of stochastic variables. For each outgoing train, the number of blocks n_r is modeled by a Poisson distribution $n_r \sim Poi(\lambda)$ where λ describes the expected value of blocks in an outgoing train. The number of railcars of each block is also Poisson distributed with $\nu_{w,r} \sim Poi(30/\lambda)$, i.e. the expected number of railcars in an outgoing train is 30. Blocks of outgoing trains are randomly assigned to incoming trains which arrive in the yard in a random period. Regarding PPS, the humping sequence of incoming trains is important to know. For this aim, the humping sequence of incoming trains is coincidental in each period.

The railcar weights are based on the railcar types used by Deutsche Bahn (2021). For each railcar type average tare weight and average load limits are calculated based on the available sub-categories. Railway lines are devided into different distance classes depending on the permitted maximum axle load and maximum linear load of a train. Because 86 % of the rail network of DB Netze are assigned to distance class D4 (maximum axle load: 22.5 tons, linear load: 8 tons/meter) (Deutsche Bahn AG, 2019), sub-categories with specification to the considered distance class D4 are involved. If there are no specifications to distance class D4, the considered sub-category is rejected. Average tare weight and average load limits for each railcar type can be found in Appendix A. Because distributions of railcar types in use are hard to find, the weights are chosen as tare weights (10 %, equals empty railcars) or a random number between tare weight plus 50 % of load limit and tare weight plus 100 % of load limit (90 %). Additional parameters of the emission model assumed in the simulation experiments are summarized in Appendix A.

In order to limit the complexity of the simulation experiments, preliminary simulation runs were conducted to screen for the most relevant problem instance parameters. It was suspected that some of the parameters have less impacts on emissions compared to other parameters. Preliminary tests revealed that the number of periods and the number of replications have only small effects on total emissions and are, thus, fixed to 20 periods and 100 runs. The number of classification tracks to be used in PPS is also to be set. As a result of preliminary tests, the number of classification tracks for PPS is reasonably set to the expected value of blocks to be shunted.

Based on the preliminary test, most relevant parameters affecting GHG emissions during shunting are the numbers of incoming and outgoing trains as well as the expected number of blocks. The number of incoming and outgoing trains is varied from 10 to 100 in steps of 10. The expected number of blocks ranges from 5 to 30 in steps of 5. For each simulation setting total GHG emissions for the above-mentioned sorting strategies SBT, SBB, TS, GS and PPS are calculated. The simulation experiments are coded in Java and run on a AMD Ryzen 7 4800H with 8 GB memory.

4.2. Results

For each combination of number of incoming trains, number of outgoing trains and expected number of blocks (λ) the simulation shows that either SBB or SBT works best w.r.t. total GHG emissions. The results can be found in Table 1 and are subdivided for the three varied parameters. For reasons of clarity the tables show only single letters to identify the best sorting strategy. The corresponding emission values can be found in Appendix B.

To get an overview, the five sorting strategies of Table 1 are first assessed by their average relative deviation to the best sorting strategy in terms of total GHG emissions, see Fig. 10. I.e. over all simulation settings, the average deviation to the corresponding best sorting procedure is calculated. The average deviations for all sorting porcedures are depicted in Fig. 10. The total average deviation of SBB is close to 0 as it is the best scenario in most cases. SBT, TS and GS produce higher GHG emissions on average than SBB with a surplus of 40–130% on average. PPS performs worst with an average relative performance of 300%

indicating that considering limited numbers of tracks might have a substantial effect on shunting operations.

The average results indicate that SBT and SBB work best. A detailed look at the results reveals, that if the expected number of blocks is small (5 or 10) and the number of outgoing trains is high, SBT is the optimal sorting strategy. For all other combinations, SBB is the best choice to minimize GHG emissions.

Further investigations show that PPS is the best sorting strategy in a specific scenario. In the results above blocks of outgoing trains are distributed on incoming trains over the whole 20 periods. If the interval of periods in which blocks of an outgoing train arrive at the yard comprises only two sequential periods and the number of outgoing trains are low, PPS is the best sorting strategy. This result can be found in Table 2 and the emission values can be found in Table C. For the remaining parameter combinations in this setting SBB is again the best sorting strategy.

To assess the simulation results from another perspective, an additional KPI is introduced. As time is another crucial parameter in shunting operations, the average number of pulled back railcars is a good indicator to evaluate the speed of shunting, i.e. the less railcars are pulled back the less time is needed for shunting. The best sorting strategy w.r.t. minimal average number of pulled back railcars in the same experimental design as above can be found in Table 3. Again, for reasons of clarity the sorting strategies are represented by a single letter and the average number of pulled back railcars for the best sorting strategy can be found in Appendix D. At first sight the results are similar to the results in Table 1, i.e. SBT and SBB are again the best sorting strategies w.r.t. minimal average pulled back railcars. At second glance the behaviour of the best sorting strategy by increasing expected number of blocks per train changes. If the expected number of blocks increases, SBT remains the best sorting strategy in half of all cases. Other strategies (TS, GS, PPS) are still never the best strategy w.r.t average pulled back railcars. To sum up, SBT is not the best sorting strategy w.r.t. to minimal emissions for an increasing expected number of blocks per outgoing train but shunting time is presumably shorter compared to SBB.

Likewise the results of the experiment with two sequential periods of incoming blocks show a different behaviour. Comparing these results, see Table 4, with previous results, see Table 2, leads to the conclusion that PPS is never the best sorting strategy w.r.t. minimal average pulled back railcars. The numbers of average pulled back railcars for the best sorting strategies can be found in Table E. Hence, PPS is the best sorting strategy w.r.t. minimal emissions for a small number of outgoing trains but shunting needs presumably more time compared to SBB.

5. Outlook

The aim of this article is to find the emission-optimal sorting strategy in shunting yards. For this purpose, sorting strategies well known in literature are embedded in a rolling horizon approach. To assess the sorting strategies' total GHG emissions, performance functions are derived analytically. Experiments with the rolling horizon model results in a simulation study which is conducted for different parameter settings (varying number of incoming/outgoing train,…). The simulation shows that depending on the parameter constellation SBT, SBB, or PPS are the best sorting strategies w.r.t. total emissions. The behaviour of the best sorting strategy varies if the emissions results are compared with the 'average number of pulled back railcars' results. This indicates that shunting operations management has a simple instrument at hand to reduce GHG emissions from shunting operations by selecting a proper sorting strategy.

As studying environmental performance of shunting operations in a rolling horizon approach is new to literature, some further research questions are open. A general assumption to apply SBT, SBB, TS or GS is the unlimited number of classification tracks. In the future, the model can be expanded by incorporating a limited numbers of classification tracks. Some parameters of the emission model are derived by the marshalling yard in Halle (Saale). Studying other marshalling yard layouts, particularly regarding distances and availability of departure tracks, may lead to further insights in environmental shunting performance. In the above obtained results TS and GS are never the best sorting strategies w.r.t. minimal emissions. In a setting with limited numbers of classification tracks, this may change. Particularly, changing the sorting strategy dynamically depending on the number of ingoing and outgoing trains as well as available classification tracks may lead to further potentials for GHG minimization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Appendix A. Railcar types and technical parameters

Tables 5 and 6.

Appendix B. Tables of emission values

Emission values of the best sorting strategy for expected railcar numbers 5 to 30 can be found in Tables 7–12.

Appendix C. Tables of emission values for two sequential periods

See Tables 13–15.

Appendix D. Tables of average pulled back railcar values

Average pulled back railcar values of the best sorting strategy for expected railcar numbers 5 to 30 can be found in Tables 16–21.

Appendix E. Tables of average pulled back railcar values for two sequential periods

See Tables 22–24.

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