Journal of Rail Transport Planning & Management 33 (2025) 100498

Contents lists available at ScienceDirect

Journal of Rail Transport Planning & Management

journal homepage: www.elsevier.com/locate/jrtpm

Full Length Article

A study on sorting strategies in marshaling yards with a limited number of tracks and track capacity

Max Zien [a,*], Thomas Kirschstein [b], Christian Bierwirth [a]

[a] School of Economics and Business, Martin-Luther-University Halle-Wittenberg, Große Steinstraße 73, 06108 Halle(Saale), Germany
[b] Fraunhofer Center for International Management and Knowledge Economy IMW, Neumarkt 9, 04109, Leipzig, Germany

ARTICLE INFO

Keywords:
Marshaling yard
Sorting strategy
Rolling horizon
Temporal decomposition

ABSTRACT

In marshaling yards, freight wagons are sorted from inbound trains to outbound trains for further transport. To organize an efficient shunting process, sorting strategies are proposed in the literature. The application of sorting strategies is generally restricted by the number of classification tracks and their lengths. This can lead to difficult-to-implement or even inoperative sorting plans. To handle limited track capacity, we decompose the shunting process into a series of consecutive periods of time resembling timetables of inbound trains. A heuristic is used in every period to decide on the postponement of inbound trains when track capacity is scarce. This way, sorting strategies become applicable on a rolling time basis. A strategy is said to solve a shunting task when it enables building all outbound trains within a given time horizon. We examine the performance of five well-known sorting strategies for a large set of shunting tasks within a computational study. The simulation results indicate that the sorting strategies perform differently when numbers and lengths of classification tracks vary. In conclusion, we are able to determine the most reliable strategy among the set of considered sorting strategies for a marshaling yard of a certain size.

1. Introduction

In 2020 the share of rail freight transportation in Germany has been 18% of the total transport volume, while the share of road freight transportation adds up to almost 75% (Statistisches Bundesamt, 2022). In order to reduce greenhouse gas emissions caused by road traffic continuous effort is made at the political level to shift freight traffic from road to rail (Bundesministerium für Digitales und Verkehr, 2021). In 2017, for instance, the German government published a master plan proposing, among others, measures for strengthening the rail-network infrastructure (Bundesministerium für Verkehr und digitale Infrastruktur, 2017). A building block of the plan is the modernization and expansion of marshaling yards which is crucial for improving the efficiency of rail transportation for general cargo.

The majority of rail freight transportation in Germany is related to bulk goods (Statistisches Bundesamt, 2023). Bulk goods, having a same origin and destination, are usually moved in large volumes by trains which operate in a direct traffic mode. In contrast, general cargo is moved in smaller entities and typically organized as so called wagon-load traffic or wagon-load service. To enable rail transport efficiency for general cargo, single wagons (in the following called railcars) have to be routed through the railway network by traversing marshaling yards. In these nodes, railcars or groups of railcars (called blocks) are sorted from inbound trains to outbound trains such that the transport capacity of the trains is utilized to a large extent.

* Corresponding author.
E-mail addresses: max.zien@wiwi.uni-halle.de (M. Zien), thomas.kirschstein@imw.fraunhofer.de (T. Kirschstein), christian.bierwirth@wiwi.uni-halle.de (C. Bierwirth).

https://doi.org/10.1016/j.jrtpm.2024.100498
Received 23 February 2024; Received in revised form 10 November 2024; Accepted 5 December 2024

Available online 17 December 2024

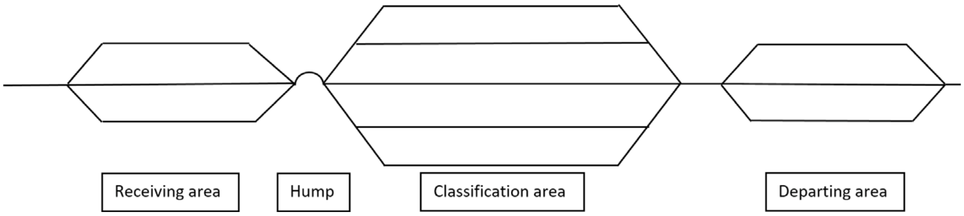

Fig. 1. Typical layout of a marshaling yard.

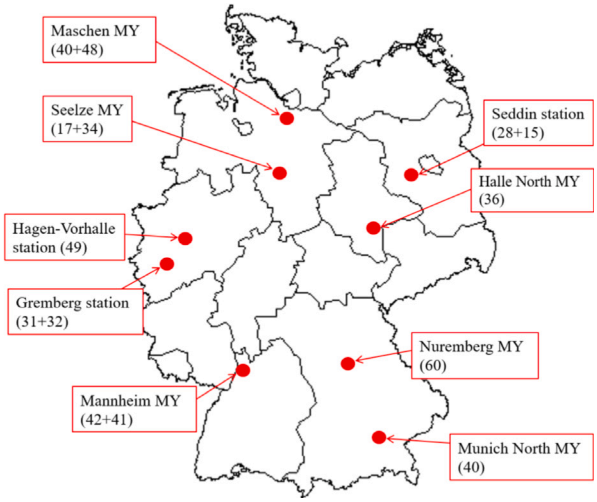

Fig. 2. Overview of Germany's major marshaling yards (MY).

Fig. 1 shows the typical layout of a marshaling yard for building trains in a wagon-load service. It consists of a receiving area, a hump, and areas for the classification and departure of trains. Inbound trains arrive on the receiving tracks. The sorting of blocks takes place on classification tracks. Departing tracks are used for building outbound trains and the preparation for departure. In some marshaling yards there is no departing area, like e.g. in Halle (Saale). Here, the preparation and sorting of outbound trains is carried out completely in the classification area. The classification tracks are then divided for a certain time into tracks designated for sorting blocks and tracks designated for collecting blocks already sorted and ready for building outbound trains. As a rule, mixed tracks are used at a marshaling yard on which railcars that cannot be directly assigned to an outbound train are temporarily parked.

In the German railway network there are nine major marshaling yards spread over the country, see Fig. 2. While the layout structure of these yards is pretty standard, they differ in size and physical capacity. The numbers appearing for the yards indicate the available quantity of classification tracks. The currently largest marshaling yard in Germany is located in Maschen (Hamburg). It has a total of 40 plus 48 classification tracks over a length of 1.5 km each. One of the most modern marshaling yards in Germany is Halle (Saale). This yard is fully automated, i.e. switching and braking operations are carried out by the railcars without human assistance.

The productivity of a marshaling yard is basically bounded by two factors. One is the physical capacity and the other is the suitability of the used sorting strategy to build outbound trains with the infrastructure at hand. This paper investigates the relation between these factors. Its contribution is twofold. First, we develop a procedure to apply sorting strategies under physical capacity restrictions, i.e. when the number and length of classification tracks in a marshaling yard are limited. It is based on a heuristic which selects a subset of inbound trains waiting at the receiving tracks to be pulled into the classification tracks. Blocks which cannot be shunted by a sorting strategy are postponed. To cope with postponed blocks, the sorting strategy is embedded in a rolling horizon model. As a second contribution we propose a method for estimating the yard productivity by determining the potential of well-known sorting strategies under variable physical restrictions. Using a period-based simulation we are able to assess the efficiency provided through a certain combination of physical capacity and a certain sorting strategy.

We make a few simplifying assumptions for the simulation: Each railcar is assigned to exactly one block and outbound train. Each block has the same priority, and there are no uncertain events that require robust planning. Train schedules are simplified by assuming that each inbound train arrives at a certain period. We further assume that outbound trains can only be formed if all associated railcars are queuing on classification tracks. If this happens, the train is formed immediately and departs, i. e. the departing period of an outbound train is the period when its last associated blocks become available. An outbound train can only depart with all its associated railcars and blocks. It is not allowed that blocks miss their dedicated connection. These assumptions result in dependencies between planners in rail yard and freight transport planning. For example, the planner who draws up the plans for single wagonload traffic must work closely with the marshaling yard planners to ensure that all connections are implemented as required by the assumptions as assignments of wagons to outbound trains that deviate from the plan are not permitted.

The paper is structured as follows. We review the literature in Section 2, revisit well-known sorting strategies in Section 3, and explain a rolling time based implementation in Section 4. In Section 5 the heuristic to handle scarce track capacity is described. A computational study is outlined in Section 6. The paper is summarized in Section 7.

2. Literature review

There is a large amount of literature dealing with the design and operation of marshaling yards. Recent overviews can be found e.g. in Gatto et al. (2009) and Deleplanque et al. (2022). In this paper we look at the organization and implementation of shunting processes for the building of trains in wagon-load services. An often used classification proposed in the literature is the distinction between single-stage and multi-stage sorting processes, which is outlined in detail below.

With single-stage sorting, railcars are rolled over the hump only once. Various objectives and models have been investigated for this type of sorting. In Jaehn et al. (2015a,b), a single-stage-sorting model is set up in which the allocation of railcars to several outbound trains is possible. The model minimizes the weighted delays of all outbound trains. Boysen et al. (2016) divide the shunting process into four steps: 1. assignment of inbound trains to receiving tracks, 2. assignment of inbound railcars to outbound trains, 3. railcar classification problem, determining a sequence for the railcars to be shunted, 4. outbound track assignment problem, assigning tracks to the outbound trains. The authors deal with Problem 2 by setting up an optimization model. It selects railcars from a set of inbound trains and assigns them to outbound trains such that the total priority value of the selected railcars gets maximized. A further objective pursued in single-stage sorting is the minimization of the number of used tracks. Dahlhaus et al. (2000a) set up a model that forms all outbound trains with as few used classification tracks as possible.

Multi-stage sorting is dealt with in the literature more often than single-stage sorting. Here, railcars are rolled over the hump and pulled back into the receiving tracks until a predefined target has been reached. Typical procedures for multi-stage sorting are the strategies described in Section 3. Optimization models have also been proposed for specific problems. The practical benefit of optimization, however, is limited given the tremendous complexity of the underlying sorting problem. Surveys on optimization models are given by Bohlin et al. (2018) and Deleplanque et al. (2022).

Many optimization models strive for the minimization of pullbacks or, more specifically, the number of railcars pulled back. Both criteria address the sorting speed, which is a proxy for minimizing the average throughput time of railcars in the yard, see Raut et al. (2019). Further criteria considered are the minimization of the number of classification tracks in use and the minimization of delay of train departures, see Preis et al. (2023). An optimization model for multi-stage sorting which takes the utilization of the yard into account has been developed by Belošević and Ivić (2018). In this model the cost for using tracks and track capacity is minimized. The optimization model proposed by Zhang et al. (2023) creates a plan for the shunting of cars and train makeup, which corresponds to Problems 2 and 3 according to the classification of Boysen et al. (2016). The authors minimize the total dwell time of railcars, i.e. the time between their arrival and departure in a marshaling yard.

Another option for the multi-stage sorting of railcars is to use mixed tracks, where blocks are moved and stored that cannot be assigned directly to an outbound train. The blocks in a mixed track have to be shunted again at a later point in time which causes considerable expenses. Methods for resolving mixed tracks are investigated by Bohlin et al. (2016) and Gestrelius et al. (2017). In practice the utilization of mixed tracks often relies on undocumented expert knowledge.

The marshaling yard layout considered in this paper differs from the full layout described above in that it has no exclusive departure area. That is why the classification area needs to be split up into tracks designated for sorting blocks and tracks designated for collecting blocks already sorted and ready building outbound trains. In such a yard, the decision on track allocation, i.e. the provision of capacity for sorting blocks and for unfinished outgoing trains, must be made in each planning period. Such layouts are found at several places in Europe, e.g. in Halle/Saale (Germany), in the Sävenäs marshaling yard at Gothenburg (Sweden) and in the Lausanne-Triage marshaling yard at Lausanne (Switzerland), compare (Gestrelius et al., 2017; Márton et al., 2009). Further layout variants are proposed and investigated in the literature. For example, Otto and Pesch (2017) examine two-sided marshaling yards where the structure shown in Fig. 1 is present in two opposing directions. Márton et al. (2009) also consider marshaling yards with two humps. In Kraft (2002), and Kraft (2003) specific yard layouts are proposed with regard to associated sorting strategies. These layouts include two or more subyards and no departure tracks.

3. Sorting strategies

The work process at a marshaling yard is as follows: As soon as a train arrives at a receiving track, the locomotive and the blocks are decoupled and pushed towards the hump. When a block reaches the top, it rolls into a classification track. The process of rolling in blocks from an inbound train is called initial humping. If an outbound train is completed after initial humping of the inbound trains, this is called single-stage sorting. Single-stage sorting is always possible if there is no block sequence prescribed for outbound trains.

If outbound trains cannot be formed through initial humping, unsorted blocks that remain on the classification tracks are pulled back into the receiving tracks and humped again into the classification tracks. This procedure might be necessary several times which is referred to as multi-stage sorting. When the blocks of an outbound train are arranged on a departing track in the desired order, they are coupled to each other and to a locomotive. From now on the outbound train is ready to leave the marshaling yard.

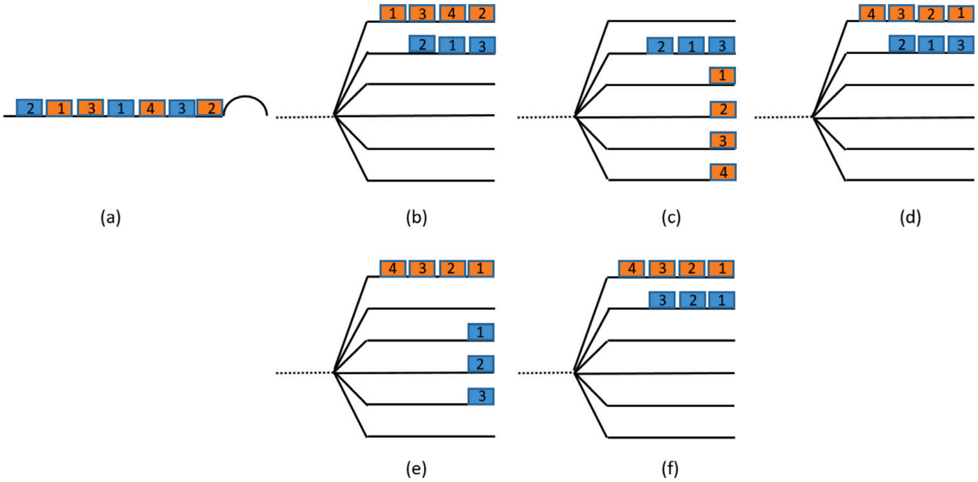

Fig. 3. Illustration of the sorting-by-train (SBT) strategy.

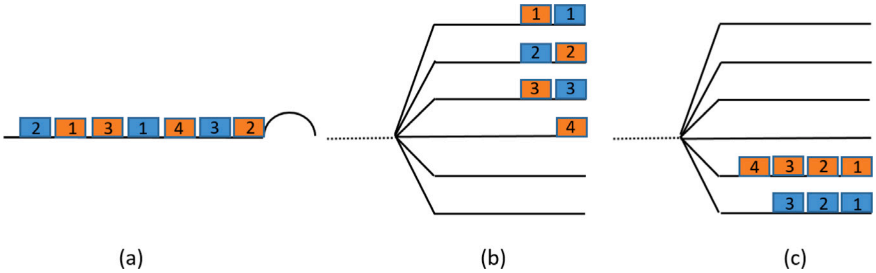

Fig. 4. Illustration of the sorting-by-block (SBB) strategy.

A systematic sorting approach for blocks is promised by genuine sorting strategies. Such methods, hereafter simply called sorting strategies, formulate a strict rule for sorting blocks. Applying such a rule iteratively allows solving basically any shunting task, provided track capacity is of no concern. This means that there is no restriction on the number of classification tracks and their lengths. It should be noted that each sorting strategy considered in this paper is applicable independent of whether the yard layout provides departure tracks or not.

We consider five strategies which are implementable in every yard layout provided physical capacity is of no concern: (i) sorting-by-train (SBT) (Daganzo, 1987a,b; Gatto et al., 2009; Deleplanque et al., 2022), (ii) sorting-by-block (SBB) (Gatto et al., 2009; Deleplanque et al., 2022), (iii) triangular sorting (TS) (Daganzo, 1987a; Gatto et al., 2009; Deleplanque et al., 2022), (iv) geometric sorting (GS) (Gatto et al., 2009; Deleplanque et al., 2022), and (v) parallel pullback sorting (PPS) (Dahlhaus et al., 2000b; Gatto et al., 2009). The strategies are illustrated below at a same shunting task. In this task we are given one inbound train with seven blocks to be sorted into two outbound trains, an orange train with four blocks and a blue train with three blocks. Numbers indicate the desired block order of the outbound trains.

SBT assembles the outbound trains one after another. During initial humping, the blocks of inbound trains which are designated to a same outbound train are shunted to a common classification track. Once all blocks of an outbound train are collected on a classification track, the outbound train can be built. Block sequences not appearing in the desired order are pulled back on separate classification tracks. The blocks are re-humped in ascending order of their position in the outbound train. With SBT, blocks are pulled back at most twice. Fig. 3(a) shows the initial state of the example, (b) the state after initial humping, (c) the state after the first pullback and re-humping, (d) the state when the orange outbound train is completely built, and (e)–(f) the corresponding splitting and building of the blue outbound train.

SBB is a simultaneous sorting strategy which means that blocks designated to different outbound trains can be collected on a same classification track. During initial humping, blocks of inbound trains having a same order position in their designated outbound trains are shunted to a common classification track. These blocks are pulled back in ascending order of the block numbers. During re-humping, the blocks are rolled on separate classification tracks designated to their outbound trains. With SBB, each block is pulled back exactly once. Fig. 4(b) shows the state reached after initial humping, and (c) the final result after four pullbacks.

TS and GS are simultaneous sorting strategies as well. They work identically with the exception of the initial humping. Differences only show up when inbound trains have ten blocks or more.

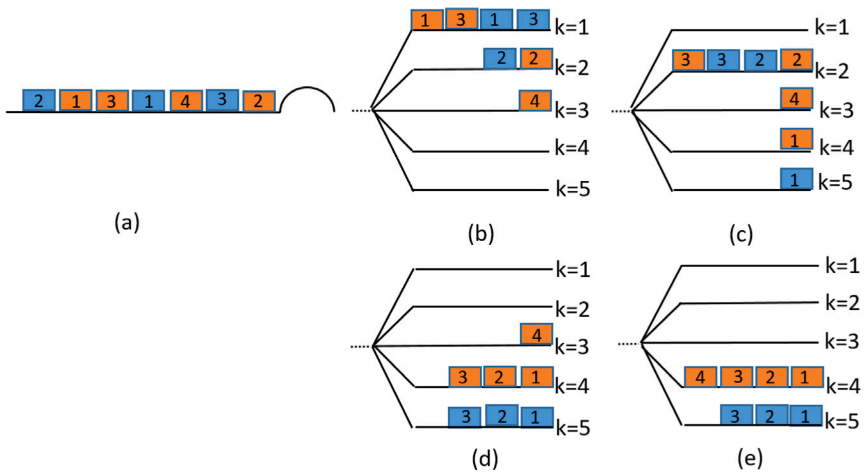

Fig. 5. Illustration of the triangular sorting (TS) and geometric sorting (GS) strategy.

Thus, for our example, TS and GS work in analogous manner. Initially both strategies assign blocks with certain positions in the outbound trains to a same classifications track. For instance, GS generates a geometric pattern where blocks with positions $k + i \cdot 2^k$, $(i = 0, 1, 2 \ldots)$ are assigned to track $k = 1, 2, \ldots$. This initial assignment ensures that no block needs to be pulled back more than twice. Then the blocks in the occupied classification tracks are pulled back and rolled in again, starting with track $k = 1$. Fig. 5(b) shows the common state generated by TS and GS through initial humping. Afterwards, three pullback operations are required to reach the desired final state as is shown in Fig. 5(c)–(e).

A modified version of triangular and geometric sorting is set up by Kraft (2002), called continuous multiple stage sorting. All railcars of an outbound train are numbered as before, starting at 1. However, the assignment of railcars to the classification tracks is offset, e.g. cars 1, 3, 5, …of a first outbound train are moved to the first classification track, while cars 1, 3, 5, …of a second outbound train are pushed onto the third classification track, and so on. In this way, trains can be completed and leave the marshaling yard while other trains are still being assembled.

PPS differs from the other strategies as it operates on a preset number of classification tracks. Tracks not used for classification serve as departing tracks. Dahlhaus et al. (2000b) originally introduced PPS for one inbound and one outbound train.

A generalization of PPS for multiple inbound and outbound trains is as follows. Assume the number of classification tracks is set to $\bar{k}$. Let the blocks of outbound train $r \in R$ be numbered consecutively by $b = 1, 2, \ldots, n_r$. Then, outbound train r is formed through the following iteration:

1. Roll in block $b = 1, 2, \ldots, n_r$ onto track $1 + \left(\left(\left\lceil \frac{b}{2^{i-1}} \right\rceil - 1 \right) \ mod \ \bar{k} \right)$,
2. Pullback blocks from the classification tracks in descending order $\bar{k}, \bar{k} - 1, \ldots, 1$.

PPS progresses by a series of parallel sorting steps $i = 1, 2, \ldots$ and terminates when the desired order of all trains $r \in R$ has been achieved. The number of pullback operations required to build an outbound train is $\lceil log_{\bar{k}} n \rceil$ with n denoting the maximum number of blocks among all outbound trains, see Zien and Kirschstein (2023). PPS is illustrated in Fig. 6 for $\bar{k} = 2$ classification tracks. State (b) is reached by Step 1 in the first iteration, State (c) by Step 2 in the first iteration, State (d) by Step 1 in the second iteration, and so forth. Note that the final state is reached after the second pullback operation and the humping that followed.

4. Rolling horizon approach

Trains arrive and depart at marshaling yards according to timetables. Before a specific outbound train can depart, all inbound trains with blocks belonging to this outbound train have to been arrived. Thus, we call an outbound train constructable if all blocks needed to build the train are available in the yard, and non-constructable otherwise. To minimize delays for train departures, so far non-constructable trains often need to be built immediately when missing blocks arrive. To fasten this process, sorting strategies enable assembling trains dynamically.

We investigate this issue using a rolling time horizon approach. It subdivides the planing horizon into a series of consecutive time periods. We start with an empty classification area and choose one of the sorting strategies considered above. We suppose that inbound trains arrive at the receiving area of the yard at the beginning of every period. We further suppose that capacity of the receiving area is of no concern. Thus, all newly arrived inbound trains can be initially humped by the sorting strategy under use. The rest of the period is spent with sorting blocks on classification tracks. Constructable trains are completed and depart at the end of the period. Blocks of non-constructable trains remain on classification tracks and are taken into account again in the forthcoming period. To assess the dynamic behavior of a sorting strategy, we count the number of outbound trains completed within a given

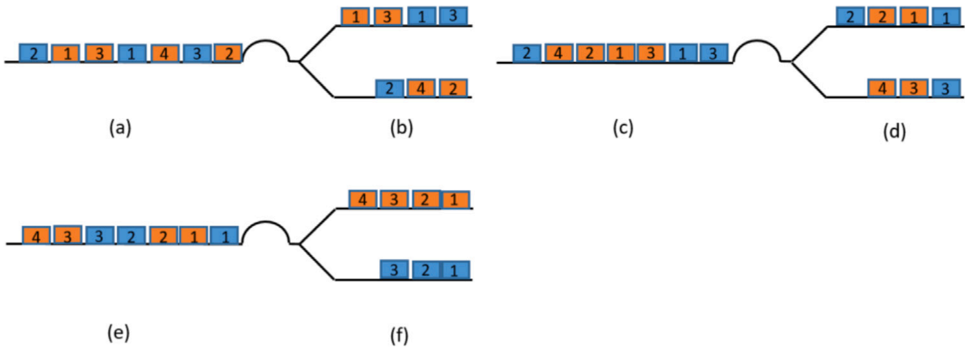

Fig. 6. Illustration of the parallel pullback sorting (PPS) strategy.

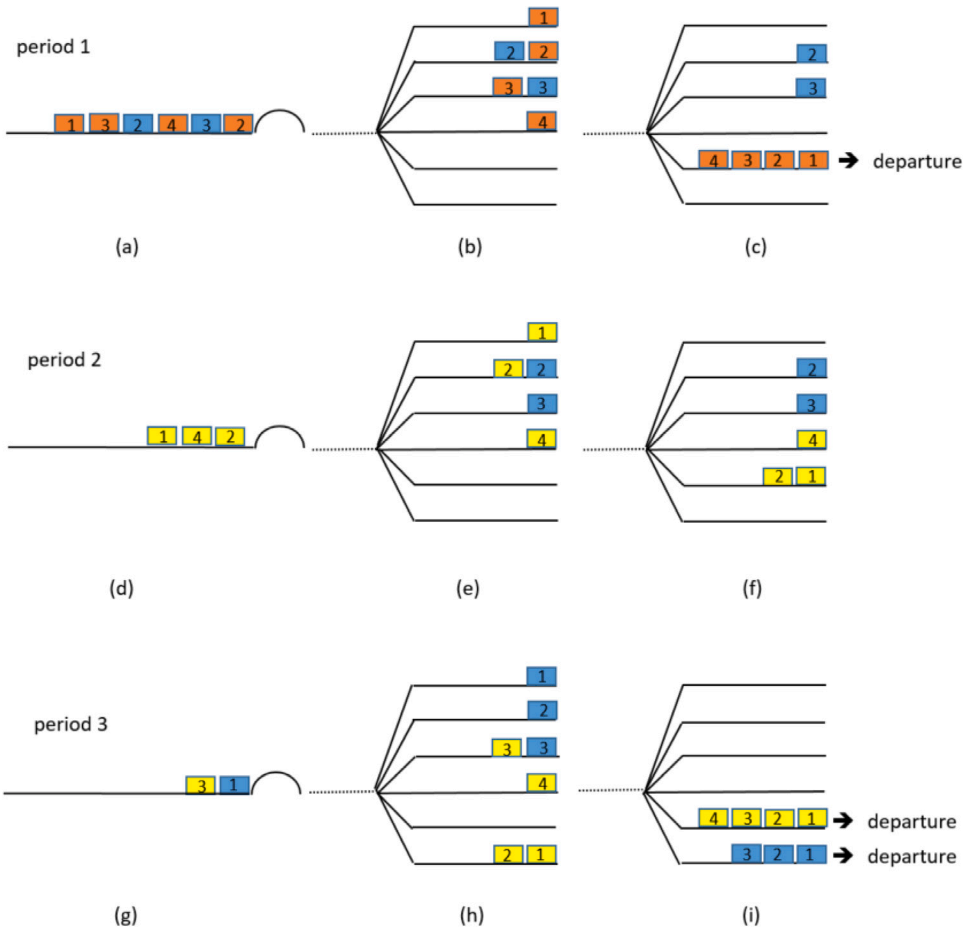

Fig. 7. Illustration of SBB within a rolling time horizon framework.

number of consecutive periods. Note that for this purpose it is not necessary to schedule the shunting operations in detail. Also roll-in times of inbound trains, departure times of outbound trains, etc. do not have to be determined as in a classical or rolling horizon based scheduling simulation. Of course, flowcharts can be created to compile the departing trains from the simulation results if required. A detailed description of the procedure and a discussion on special features of the five sorting strategies is given in Zien and Kirschstein (2023).

Fig. 7 illustrates the approach for SBB and a yard layout without departure tracks. In each of three consecutive periods, a single inbound train arrives at the yard. With the first train, the orange outbound train is constructable while the blue one is not, see Fig. 7(a). Initial humping with SBB sorting is shown in Fig. 7(b). The following pullback operations complete the building of the

Table 1
Definition of parameters and sets for shunting tasks.

σ	Sorting strategy from the set $\{SBT, SBB, TS, GS, PPS\}$
I	Set of inbound trains
R	Set of outbound trains
n_r	Number of blocks of train $r \in R$
$n_{w,r}$	Number of railcars of block $w \in \{1,\dots n_r\}$ of train $r \in R$
$W(j,t)$	Set of blocks that contains: (1) already shunted and scheduled blocks on the classification tracks, (2) included and scheduled blocks of outbound trains which are in inbound train j
G	Number of available classification tracks
G_{cap}	Railcar capacity of a classification track corresponding to the track length
$G_{dep}(j,t)$	Number of departing tracks needed in period t to build all outbound trains that contain a block in $W(j,t)$; $G_{dep}(j,t) = \lvert R^{\sigma}_{all}(j,t)\rvert$
$G^{\sigma}_{max}(j,t)$	Number of sorting tracks needed by σ in period t to sort all blocks of $W(j,t)$ when track capacity is neglected
$G^{\sigma}_{sor}(j,t)$	Number of sorting tracks needed by σ in period t to sort all blocks of $W(j,t)$; $G^{\sigma}_{sor}(j,t) \geq G^{\sigma}_{max}(j,t)$
$I^{\sigma}_{rec}(t)$	Set of inbound trains on the receiving tracks generated by σ at the beginning of period t; $I^{\sigma}_{rec}(t) \subset I$
$I_{arr}(t)$	Subset of $I^{\sigma}_{rec}(t)$ containing trains arriving in period $t-1$; $I_{arr}(1) = I^{\sigma}_{rec}(1)$
$I^{\sigma}_{cho}(t)$	Ordered subset of $I^{\sigma}_{rec}(t)$ containing trains to hump in period t as depending on σ
$R_{out}(j)$	Set of outbound trains containing at least one block in the inbound train $j \in I$
$R_{npr}(j)$	Subset of $R_{out}(j)$ containing outbound trains not present on the classification tracks
$R^{\sigma}_{cla}(t)$	Set of outbound trains generated by σ containing at least one block on the classification tracks in period t
$R^{\sigma}_{all}(j,t)$	Set of outbound trains generated by σ that are already on the classification tracks with at least one block in period t or rolled in as inbound train j; $R^{\sigma}_{all}(j,t) = R^{\sigma}_{cla}(t) \cup R_{npr}(j)$
$\bar{n}^{\sigma}(j,t)$	Largest block number of all trains from $R^{\sigma}_{all}(j,t)$; $\bar{n}^{\sigma}(j,t) = max\{n_r \mid r \in R^{\sigma}_{all}(j,t)\}$

orange train and leaves tracks 2 and 3 occupied, see Fig. 7(c). With the second inbound train arriving in period 2, no further train is constructable, see Fig. 7(d)–(f). The two missing blocks arrive at the yard with the third inbound train, see Fig. 7(g). The blue and the yellow train are constructable now. In total, three trains depart in the planning horizon. The numbers of blocks pulled back in period 1 to 3 are 6, 3, and 5, respectively. Hence, a total of 14 blocks is pulled back when SBB is used on a rolling time basis.

In a static environment disregarding time periods, the three inbound trains are sorted after the last inbound train has arrived in period 3. In this case, SBB generates 11 pullbacks of blocks which is a little less than in the dynamic rolling horizon approach. However, a delay is caused for the orange train, originally departing in period 1. Moreover, SBB has also prearranged blocks of the blue and yellow train which presumably leads to faster shunting in period 3.

5. Sorting strategies under capacity restrictions

Sorting strategies do not care for the capacity requirements of a marshaling yard. Thus, we develop a procedure to use sorting strategies under a limited number of tracks and track lengths. It is based on a heuristic which determines a subset of the waiting inbound trains that can be humped in a period without exceeding the currently available capacity. Some preparation steps are different for the sorting strategies which is considered in 5.1. The heuristic itself is presented in 5.2.

5.1. Preparation

Limitations in track capacity can effect that not every train waiting on a receiving track can be rolled into the classification area. Inbound trains can only roll in if they do not hinder the shunting process carried out by the sorting strategy in use. We call a sorting strategy executable with regard to an inbound train, if the inbound train can be disassembled and assigned to classification tracks according to the strategy's instructions without violating a capacity constraint. Suppose for instance SBB has produced a state where the sorting tracks which are designated for blocks having a same position in the respective outbound trains are fully occupied. Suppose further no empty track to be opened is available. Then SBB is not executable for such trains.

The notation used for capturing formal conditions when a sorting strategy $\sigma \in \{SBT, SBB, TS, GS, PPS\}$ is executable for certain trains is given in Table 1. Let I denote all inbound trains arriving within the planing horizon. The number of inbound trains available in period t using sorting strategy σ is defined recursively by

$$I^{\sigma}_{rec}(t) = \begin{cases} I_{arr}(1) & \text{for } t = 1 \\ I^{\sigma}_{rec}(t-1) \backslash I^{\sigma}_{cho}(t-1) \cup I_{arr}(t) & \text{for } t > 1 \end{cases}$$

The number of sorting tracks $G^{\sigma}_{sor}()$ required for inbound train j depends on the sorting strategy σ in use, i.e. $G^{\sigma}_{sor}()$ needs to be determined separately for every σ.

SBT. Given a classification track can accommodate all the cars of the largest outbound train, track length is not a critical factor under SBT. Generally, the number of sorting tracks $G^{SBT}_{sor}()$ required by SBT corresponds to the largest block number across all outbound trains containing blocks in $W()$. It is calculated by

$$G^{SBT}_{sor}(j,t) = max\{n_r \mid r \in R^{\sigma}_{all}(j,t)\}.$$

With strategies σ other than SBT, the number of required tracks depends on the number of railcars σ attempts to assign to a certain sorting track. New sorting tracks are always opened in case the car capacity of a track is exceeded. To consider this, we first compute the number $G^{\sigma}_{max}()$ of tracks required when track length is neglected. Then, for every track containing more than G_{cap} cars, we add further sorting tracks which leads to the actual number $G^{\sigma}_{sor}()$ of tracks required by strategy σ.

SBB. For SBB the term $G^{SBB}_{max}()$ corresponds to the largest block number of all trains already present on classification tracks or that will be humped in a period; also denoted as $\bar{n}^{\sigma}()$ in Table 1. The number of tracks required by SBB under capacity G_{cap} is calculated by

$$G^{SBB}_{sor}(j,t) = \sum_{i=1}^{G^{SBB}_{max}(j,t)} \left\lceil \frac{\sum_{r\in R^{SBB}_{all}(j,t)} f_{blo}(r,t,i)}{G_{cap}} \right\rceil$$

with $f_{blo}(r,t,i) = n_{i,r}$ in case $i \notin W^{SBB,r}_t$, and zero otherwise. Here, $W^{SBB,r}_t$ denotes the set of all blocks of train r that are on the associated departing track at the beginning of period t. Note that the already shunted blocks i (on track i) of all relevant trains are taken into account in the computation provided the blocks are not left on a departing track in period t. For details of determining $W^{SBB,r}_t$ see Zien and Kirschstein (2023).

TS and GS. According to Daganzo et al. (1983), the number of classification tracks required by TS without capacity limits is calculated by $G^{TS}_{max}(j,t) = \left\lfloor \sqrt{2\cdot \bar{n}^{\sigma}(j,t) - \frac{7}{4}} + \frac{1}{2} \right\rfloor$. For GS, Gatto et al. (2009) calculate this quantity by $G^{GS}_{max}(j,t) = \lfloor \log_2 \bar{n}^{\sigma}(j,t) \rfloor + 1$. Due to the similarity of TS and GS, the number of classification tracks required by the strategies under capacity limits is calculated in a uniform manner

$$G^{TS/GS}_{sor}(j,t) = \sum_{i=1}^{G^{TS/GS}_{max}(j,t)} \left\lceil \frac{\sum_{r\in R^{TS/GS}_{all}(j,t)} f_{tra}(r,t,i)}{G_{cap}} \right\rceil.$$

Here, $f_{tra}(r,t,i)$ denotes the sum of blocks collected on track i for outbound train r in period t plus those blocks of the outbound train r which have not arrived yet. For details of determining $f_{tra}(r,t,i)$ see Appendix A.

PPS. Unlike the former strategies, PPS operates on a preset number of classification tracks. Thus, it has to be examined whether the projected allocation of tracks is sufficient for sorting trains rolling in and for collecting trains ready to depart. The idea is to determine the maximum number of railcars standing on a track at a same time that still allows building all outbound trains. Let $s^r_{\bar{k}}$ denote the number of sorting steps required to complete train r if $\bar{k}$ sorting tracks are available. Furthermore, let $B(r,pss,k)$ denote the set of blocks that train r includes in sorting step pss on track k. Provided $\bar{k}$ classification tracks are projected, the number of cars of train r on track k across all sorting steps is determined by

$$m(r,k,\bar{k}) := \max_{pss=1,\dots,s^r_{\bar{k}}} \left(\sum_{w\in B(r,pss,k)} n_{w,r} \right).$$

Overall admissibility is given if

$$\max_{k=1,\dots,\bar{k}} \sum_{r\in R^{PPS}_{all}(j,t)} m(r,k,\bar{k}) \le G_{cap},$$

holds in each time period t, i.e. track capacity G_{cap} is respected by inbound and outbound trains. Furthermore, $G_{dep}(j,t) \le G - \bar{k}$ must hold for each t, meaning that a sufficient number of tracks for outbound trains is always available. Both conditions are checked by the procedure described below.

5.2. Heuristic for prioritizing inbound trains

This section describes the heuristic procedure to determine a set of inbound trains from the receiving area for which a certain sorting strategy is executable. At first, all inbound trains present at the beginning of a period are examined in decreasing order of the train length to see whether humping into the classification tracks is executable by the strategy. All selected inbound trains then are humped into the classification tracks in descending order according to the number of railcars. We intend to roll in longer trains earlier into the receiving area which performs a kind of greedy behavior. The idea is to involve as many cars as possible in the sorting process of a period in order to increase the average number of outbound trains completable in the period. This in turn effects that trains can leave the marshaling yard earlier. Note that other priority rules might be used as well like prioritizing the most homogeneous train, i.e. the train with the fewest number of outbound destinations, or the like. After all selected inbound trains have been rolled into the classification tracks, the formation of outbound trains begins. A sketch of the heuristic is shown in Alg. 1.

The procedure pays attention to the number of tracks available in the classification area. Recall that it is split into tracks for sorting blocks and departing tracks for building outbound trains. After selecting an inbound train j, the heuristic checks whether or not the sum of required sorting and departing tracks exceeds the classification track capacity if train j rolls in. This is done by verifying whether condition

$$G^{\sigma}_{sor}(j,t) + G_{dep}(j,t) \le G$$

Algorithm 1 Heuristic prioritizing of inbound trains in period t

while $I^{\sigma}_{rec}(t) \neq \emptyset$ **do**
  Choose train $j \in I^{\sigma}_{rec}(t)$ with the most railcars, choose arbitrarily in case of tie;
  if σ is executable for inbound train j **then**
    Add inbound train j to $I^{\sigma}_{cho}(t)$;
    if train j contains blocks of outbound train $i \in R_{npr}(j)$ **then**
      Add outbound trains i to $R^{\sigma}_{cla}(t)$;
    end if
  end if
  Delete j from $I^{\sigma}_{rec}(t)$;
end while

holds in period t under sorting strategy σ, as outlined in detail above. The procedure also takes the track lengths into account. When a track's capacity is exceeded, an additional classification track is opened if available. To determine the required number of tracks and track capacity for trains whose formation has already begun (i.e. trains that are already represented on the classification tracks with at least one car), all existing and scheduled railcars of these trains are taken into account. This means, for example, that if a train has only one car on the classification tracks, its railcars that have not yet arrived are included when determining the available number of tracks and track capacity. This ensures that when rolling in railcars of new trains (i.e. trains that do not yet have cars on the classification tracks), the formation of trains that have already started is not interrupted and no deadlocks occur, meaning that it is no longer possible to form a train.

In the period-based simulation environment, Alg. 1 is executed at the beginning of every period. The inbound trains recorded in $I^{\sigma}_{cho}(t)$ are initially humped in period t. It can happen that not a single train is initially humped due to existing capacity limits. Then, period t ends and the following period starts with Alg. 1 again to check whether newly arrived inbound trains are executable by σ. Following initial humping, σ is executed. It modifies the state of blocks staying in the classification area according to its processing logic. Afterwards, it reserves track space for blocks expected to arrive in later periods for the completion of outbound trains currently under construction. The simulation terminates when the final period is completed. Note that due to capacity restrictions and sorting strategy some outbound trains may not be completed at the end of the planning horizon.

Fig. 8 shows a simulation example for a marshaling yard with six classification tracks and a track capacity of three railcars. The simulation applies SBB and runs over three periods with four inbound trains and five outbound trains. Inbound train *it1* arrives in period 1 and is executable by SBB. It carries railcars for the blue and the orange outbound trains *ot1* and *ot2*, see (a). After initial humping shown in (b), a pullback is carried out for each of the three tracks leading to state, see (c). For the missing car 2 of the orange train, a reservation is made and inserted in the final classification state of period 1. The blue train departs. At the beginning of period 2, two further inbound trains *it2* and *it3* have arrived at the receiving tracks, see (d). As both trains are of the same length, Alg. 1 checks them in arbitrary order for possible initial humping. While *it2* can be successfully sorted by SBB, shunting of *it3* is not possible as shown in (e) and (g). Since the track capacity of the sorting tracks accommodating s numbered 2 and 3 is exceeded, two additional sorting tracks are required. Four departing tracks are already occupied to form *ot2*, *ot3*, *ot4*, and *ot5*. In total, nine tracks are needed by SBB, which exceeds the available track capacity. Hence, *it3* is not allowed to enter in period 2, and merely *it2* is initially humped. Execution of SBB results in (f) with *ot2* departing in period 2. In period 3, inbound train *it4* has reached the marshaling yard, see (h). Alg. 1 first checks *it4*, as it is longer than *it3*. Processing the inbound trains in this sequence requires a total of three sorting tracks and three departing tracks, see (i). Hence, SBB is executable for both trains. After three final pullback operations, all outbound trains are completed for departure, see (j).

6. Simulation study

The simulation study investigates the performance of sorting strategies in marshaling yards with a limited number of tracks and limited track capacity. The design of the study is explained in Section 6.1. Results are discussed in Sections 6.2, 6.3 and 6.4.

6.1. Experimental design

A set of shunting tasks is constructed to analyze the sorting strategies performance for various layouts. For this purpose, layout parameters (number of classification tracks and track capacity) and shunting parameters (number of inbound and outbound trains, average number of blocks per outbound train) are varied.

Reasonable ranges for the layout parameters are adopted from the nine major marshaling yards in Germany, see Fig. 2. Table 2 shows the number of classification tracks of a yard which is given by a sum in cases of two-sided yards. The track lengths are assessed using Google Maps. Assuming an average car length of 25 m, the capacity of tracks belonging to a marshaling yard is derived. Based on this empirical data we vary the number of classification tracks between 15 and 60 tracks in steps of 5 and track capacity between 36 and 60 railcars in steps of 8. For PPS the number of sorting tracks ($\bar{k}$) is set to 50% of the total number of classification tracks based on preliminary experiments.

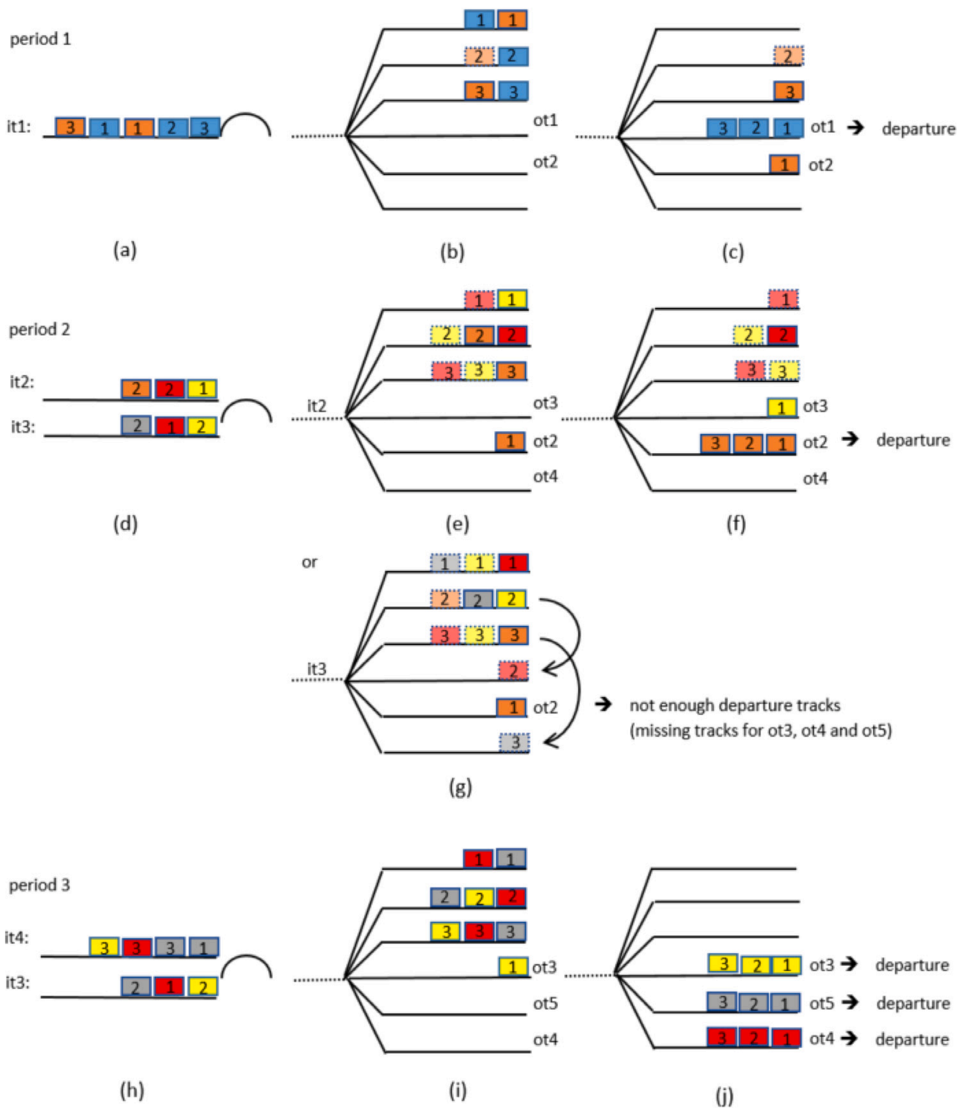

Fig. 8. Examplary illustration of Alg. 1 for SBB in a rolling horizon setting.

Table 2
Capacity of nine major marshaling yards in Germany.

Marshaling yard	Number of classification tracks	Track length (estimated) in km	Capacity (number of wagons)
Maschen (Hamburg)	40 + 48	1.5	60
Seelze (Hanover)	17 + 34	1.1	44
Seddin (Potsdam)	28 + 15	0.9	36
Halle/Saale	36	1.5	60
Hagen-Vorhalle	40	0.9	36
Gremberg (Cologne)	31 + 32	1.1	44
Mannheim	42 + 41	0.9	36
Nuremberg	60	1.1	44
Munich	40	1.1	44

In order to generate sufficiently different shunting tasks, we vary the number of inbound trains between 10 and 90 trains and the number of outbound trains between 10 and 50 in steps of 20 each. Zien and Kirschstein (2021) indicates that shunting tasks are not solvable for larger numbers of outbound trains when the layout parameters are chosen within the given ranges. To vary the number of blocks while maintaining a reasonable train length, the following procedure is used: The number of blocks n_r per outbound train r

Table 3
Overview of simulation parameters including type, range, and step size.

Parameter	Type	Range	Step size	nb. steps
Number of classification tracks	Layout	15 to 60	5	10
Number of cars per track (= track capacity)	Layout	36 to 60	8	4
Number of inbound trains	Shunting	10 to 90	20	5
Number of outbound trains	Shunting	10 to 50	20	3
Expected number of blocks per outbound train λ	Shunting	10 to 30	10	3

is drawn from a Poisson distribution with $n_r \sim Poi(\lambda)$, where λ indicates the expected number of blocks per outbound train. We vary λ from 10 to 30 in steps of 10. The number of railcars $n_{w,r}$ per outbound train r is distributed with $n_{w,r} \sim Poi\,(30/\lambda)$. Under these assumptions the number of railcars is 30 on average per outbound train. Note that there is no need for specifying the composition of inbound trains explicitly in our simulation.

The layout and shunting parameters are summarized in Table 3 including their ranges, step sizes, and derived number of steps. We construct a full-factorial design and, thus, create 1800 parameter combinations in total. Each combination is repeated 100 times by drawing the numbers of blocks and block sizes from Poisson distributions as described above. Thus, a total of 180,000 shunting tasks is generated.

In the computational experiments we simulate the behavior of the sorting strategies as described in Section 3. To get rid of considering detailed timetables for inbound trains, we randomly assign them to 20 consecutive time periods. Trains assigned to a same period are assumed to be pulled into the receiving tracks at the beginning of that period. Then, Alg. 1 decides which of the inbound trains waiting on the receiving tracks is transferred to the classification tracks. Afterwards, a sorting strategy assembles outbound trains as prescribed by the shunting task. Complete outbound trains leave the yard while uncompleted trains remain on the classification tracks for the next period. This process is repeated for each period. At last we calculate the solution rate of a shunting task defined as the share of outbound trains that have left the marshaling yard. In general, a marshaling yard strives to ensure that all outbound trains are formed within a period of time. We therefore also examine how many of the shunting tasks have been completely solved. I.e. all outbound trains have been formed and the solution rate is 100%. It should be mentioned here that a period of time consists of the times of the individual periods and this in turn is determined by the times for sorting blocks and assembling the outbound trains and is therefore variable. If many blocks are sorted and many outbound trains are built, the period of time is longer than if fewer blocks are sorted and fewer outbound trains are built.

The following study aims to explore how variations in shunting parameters impact the effort of shunting. Our goal is to understand the relationship between specific shunting parameters and the efficiency of a marshaling yard, reflected by the solution rate. Furthermore, we investigate the effects of changes solely in layout parameters (without considering shunting parameters) on the solution rate. Putting focus on layout parameters provides insights into the way they influence the solution rate. This allows for a more commonly understood perspective on the role of yard capacity in enhancing shunting processes.

6.2. Variation of a single parameter

This section examines the impact of layout and shunting parameters on the solution rate and the solution rates for completely solved shunting tasks. Detailed results of the simulation experiments are provided as supplementary materials for the solution rates (Data-1) and the solution rates for completely solved shunting tasks (Data-2). Table 4 shows the average solution rate obtained by each of the five strategies when a single parameter varies. Equivalently, the solution rates for completely solved shunting tasks can be found in Table 5. Note that the rates are given in percent and averaged over all combinations of the other parameters given in Table 3. For example, the average solution rate of SBT (=0.94) observed for 15 classification tracks represents the mean solution rate obtained in simulation runs with 15 classification tracks (considering all combinations of track capacity, number of inbound trains, number of outbound trains and average number of blocks per outbound train). The equivalent value for SBT in Table 5 (=0.03) indicates that on average 0.03% of all shunting tasks are completely solved across all shunting tasks with 15 classification tracks.

A closer look at the solution rates in Tables 4 and 5 shows that they are very similar. This leads to the conclusion that most shunting tasks are solved completely. Otherwise, the solution rates in Table 4 would deviate strongly upwards compared to the solution rates in Table 5. Due to the similar solution rates, the following statements are valid to solution rates and solution rates for completely solved shunting tasks.

It can be seen that the average solution rate improves when the number of classification tracks or the track capacity increases. The average solution rates also improve, even if only slightly, when the number of inbound trains increases. This observation appears reasonable because a same number of blocks is distributed along an increasing number of inbound trains. Hence, inbound trains have less blocks on average which in turn eases solving a shunting task. The more outbound trains are to be sorted, the more difficult shunting tasks become. Thus, average solution rates decline. For the same reason, average solution rates decline when the average number of blocks per outbound train increases.

The trends roughly outlined above correlate with the common understanding about what makes a shunting task hard to solve. It is worth mentioning that the observed trends hold for each of the five sorting strategies. The efficiency of the strategies, however, differs strongly. Overall, SBT and SBB perform quite similar just as TS and GS do. PPS is clearly outperformed by the other strategies. Looking at the number of classification tracks, TS and GS dominate SBT and SBB for up to 35 tracks. With more tracks available

Table 4
Average solution rates clustered by parameters.

Parameter	Value	SBT	SBB	TS	GS	PPS
Classification tracks	15	0.94%	0.94%	1.83%	1.99%	0.67%
	20	2.21%	2.21%	6.68%	5.75%	1.81%
	25	8.65%	8.43%	19.61%	14.01%	3.56%
	30	11.15%	11.13%	28.46%	23.86%	8.07%
	35	15.30%	15.30%	33.34%	31.85%	9.37%
	40	33.71%	33.34%	33.34%	33.34%	10.61%
	45	40.03%	33.46%	33.42%	33.36%	11.74%
	50	44.24%	35.27%	34.83%	33.78%	15.24%
	55	45.11%	40.16%	38.09%	36.09%	18.27%
	60	67.01%	48.97%	42.15%	39.24%	37.21%
Track capacity	36	26.79%	21.26%	24.00%	22.18%	9.37%
	44	26.85%	22.25%	25.53%	24.34%	11.05%
	52	26.82%	23.08%	28.46%	26.25%	11.86%
	60	26.89%	25.10%	30.71%	28.55%	14.44%
Number of inbound trains	10	25.95%	21.73%	25.81%	24.07%	10.27%
	30	26.26%	22.15%	26.47%	24.61%	10.85%
	50	26.59%	22.70%	27.05%	25.13%	11.48%
	70	27.19%	23.45%	27.75%	25.92%	12.23%
	90	28.20%	24.58%	28.81%	26.93%	13.56%
Number of outbound trains	10	61.49%	61.41%	76.97%	73.25%	33.64%
	30	18.92%	7.36%	4.55%	2.74%	1.40%
	50	0.11%	0.00%	0.00%	0.00%	0.00%
Expected blocks per outbound train λ	10	39.02%	32.33%	33.35%	31.49%	22.59%
	20	21.50%	18.93%	25.48%	23.74%	8.22%
	30	20.00%	17.51%	22.69%	20.76%	4.24%

Table 5
Average solution rates for completely solved shunting tasks clustered by parameters.

Parameter	Value	SBT	SBB	TS	GS	PPS
Classification tracks	15	0.03%	0.03%	0.81%	1.06%	0.01%
	20	1.38%	1.38%	6.45%	5.42%	0.49%
	25	8.49%	8.27%	19.53%	13.92%	2.34%
	30	11.08%	11.06%	28.42%	23.81%	7.72%
	35	15.26%	15.26%	33.33%	31.87%	9.41%
	40	33.60%	33.33%	33.33%	33.33%	10.41%
	45	39.89%	33.43%	33.37%	33.33%	11.43%
	50	44.23%	35.15%	34.71%	33.67%	14.93%
	55	45.09%	40.09%	38.00%	35.96%	17.97%
	60	66.87%	48.94%	42.08%	39.14%	37.13%
Track capacity	36	26.52%	21.03%	23.80%	21.98%	8.75%
	44	27.98%	22.95%	25.10%	24.15%	10.82%
	52	27.99%	23.89%	27.45%	25.71%	11.55%
	60	28.03%	26.08%	29.90%	27.51%	14.28%
Number of inbound trains	10	25.95%	21.73%	25.80%	24.06%	10.26%
	30	26.24%	22.13%	26.44%	24.59%	10.76%
	50	26.49%	22.62%	26.99%	25.04%	11.24%
	70	26.89%	23.19%	27.52%	25.68%	11.63%
	90	27.38%	23.80%	28.26%	26.39%	12.04%
Number of outbound trains	10	60.87%	60.80%	76.57%	72.83%	32.16%
	30	18.85%	7.29%	4.45%	2.63%	1.40%
	50	0.06%	0.00%	0.00%	0.00%	0.00%
Expected blocks per outbound train λ	10	38.33%	31.69%	32.88%	30.99%	21.33%
	20	21.45%	18.88%	25.47%	23.72%	8.00%
	30	20.00%	17.51%	22.67%	20.75%	4.22%

SBT and SBB begin dominating TS and GS. SBT and SBB perform worse than TS and GS for 35 and fewer classification tracks, as the number of classification tracks required increases more when SBT and SBB are used than with TS and GS. The impact of track capacity is almost null for SBT. For the other strategies solution rates improve by just a few percent when track capacity changes from 36 railcars to 60 railcars. The number of inbound trains to be sorted has only little effect on the performance of a strategy. A crucial driver is block fragmentation of inbound trains as is reflected by the number of blocks expected for the outbound trains. With an increase from 10 blocks to 30 blocks, the solution rates of SBT and SBB reduce by almost 50%. For TS and GS it is merely one third which indicates that these strategies get more powerful when outbound trains are composed of many blocks. The number

Table 6
Average number of handlings.

	SBT	SBB	TS	GS	PPS
Average number of pullbacks per shunting task	28.52	9.94	6.38	6.29	5.86
Average number of rehumped cars per pullback	4.7	10.34	30.23	35.38	11.96
Average number of rehumped cars per shunting task	134.04	102.78	192.87	222.54	70.09

of outbound trains to be formed within 20 periods has clearly the strongest influence on the solution rates. TS and GS are able to solve about 75% of the shunting tasks with 10 outbound trains while SBT and SBB merely solve a bit more than 60%. With 30 outbound trains, the solution rates of all strategies drastically decline, but now SBT and SBB are dominating TS and GS. With 50 outbound trains the strategies fail solving the shunting tasks in almost every case.

The above results can be used to estimate which sorting strategy should be used for which marshaling yard layout or which type of shunting task. The actual shunting effort can be estimated using handlings like average number of pullbacks per shunting task and the average number of rehumped cars per pullback, see Table 6. If a shunting task is solved with SBT, almost five times as many pullbacks must be carried out compared to TS and GS. On the other hand, only just under 1/5 and 1/6 of railcars are shunted per pullback compared to TS and GS respectively. The choice of sorting strategy for a marshaling yard layout is therefore associated with a high number of pullbacks or a high number of rehumped railcars. Only SBB as one of the dominant sorting strategies leads to a more balanced number of pullbacks and rehumped railcars compared to other sorting strategies. If the average number of pullbacks per shunting task and the average number of rehumped cars per pullback are multiplied, the result is the average number of rehumped cars per shunting task, see Table 6. If this key figure is compared for all sorting strategies, the sorting strategy SBB (apart from PPS) leads to the lowest average number of railcars to be pulled back per shunting task. The sorting strategies SBT, TS and GS, on the other hand, lead to a higher average number of railcars pulled back per shunting task and are unbalanced compared to the average number of pullbacks per shunting task and average number of rehumped railcars per pullback. It can be deduced from this that the more balanced the key figures are, the lower the total number of railcars to be pulled back.

As the results from Tables 4 and 5 are similar, Table 5 is not considered below, i.e. the following results relate exclusively to the solution rates from Table 4.

6.3. Impact of the number of classification tracks

To get deeper insights into the strategies' efficiency in solving shunting tasks we analyze the influence of physical capacity under different workload conditions met at a marshaling yard. For this purpose the simulation experiments are clustered as follows: Shunting tasks with 10 outbound trains are solved by all sorting strategies for the most part. Therefore, we refer to this class of tasks as the moderate workload scenario. In contrast, shunting tasks with 30 outbound trains represent the heavy workload scenario where sorting strategies are successful just occasionally. With 50 outbound trains, the workload becomes overwhelming for marshaling yards ranging in the considered order of physical capacity. As all strategies fail solving those tasks, the outcome of the corresponding experiments is neglected in the further evaluation.

Shunting under moderate workload. The solution rates of the shunting tasks with 10 outbound trains is analyzed regarding the available number of classification tracks. We divide this subset of tasks into ten classes where the number of tracks ranges from 15 to 60 in steps of five. Each class contains 60 shunting tasks (varying the number of inbound trains, the number of average blocks per outbound train, and the track capacity). The average-in-class solution rates are illustrated in boxplots shown in Fig. 9 for 15 to 30 tracks, and Fig. B.1 for 35 to 60 tracks.

The boxplots again verify that the average solution rates improve when the number of classification tracks increases. Apart from a few outliers, however, there is little difference observable between the sorting strategies within the class of 15 classification tracks. For 20 tracks, TS and GS deliver a broader spread of raising solution rates with the median still close to zero. For 25 tracks, the median of the solution rates reached by TS already approaches 90%. For 30 tracks both, TS and GS, solve the task class almost perfectly. It is noticeable that the other strategies follow TS and GS slowly. Even though the spread of solution rates grows with an increasing number of classification tracks, the medians achieved remain pretty low. For more than 35 tracks, SBT and SBB solve all task classes perfectly just as TS and GS do, see Fig. B.1 in the appendix. Only PPS does hardly benefit from a higher number of tracks available.

For a practical use of the sorting strategies, it can be deduced that TS should be chosen most likely when the workload is moderate and the area of classification tracks appears to be small. With a larger number of tracks available, the differences observed between the strategies increasingly diminish. Merely PPS is struggling hard and able to solve the tasks reliably not until 60 tracks are provided in the marshaling yard.

Shunting under heavy workload. A different picture results from the experiments when 30 outbound trains are supposed to be built in a marshaling yard within 20 periods. The average-in-class solution rates measured under heavy workload for 15 to 40 tracks are shown in Fig. C.2, and for 45 to 60 tracks in Fig. 10.

None of the sorting strategies is able to handle a heavy workload with 40 classification tracks or less. At 45 tracks, a significant amount of tasks is solved by SBT while the average-in-class solution rates of the other strategies is almost null. SBB is following

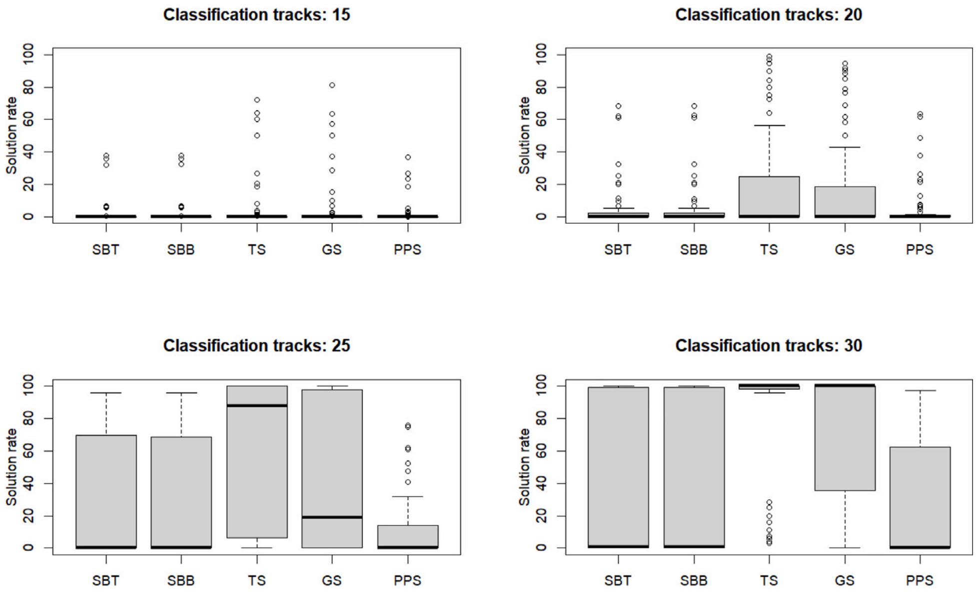

Fig. 9. Solution rates under moderate workload and 15 to 30 classification tracks. Boxplots with medians (black bold line), the box (gray) limited by the lower (25%) and upper (75%) quantile, the whiskers and the outliers (dots).

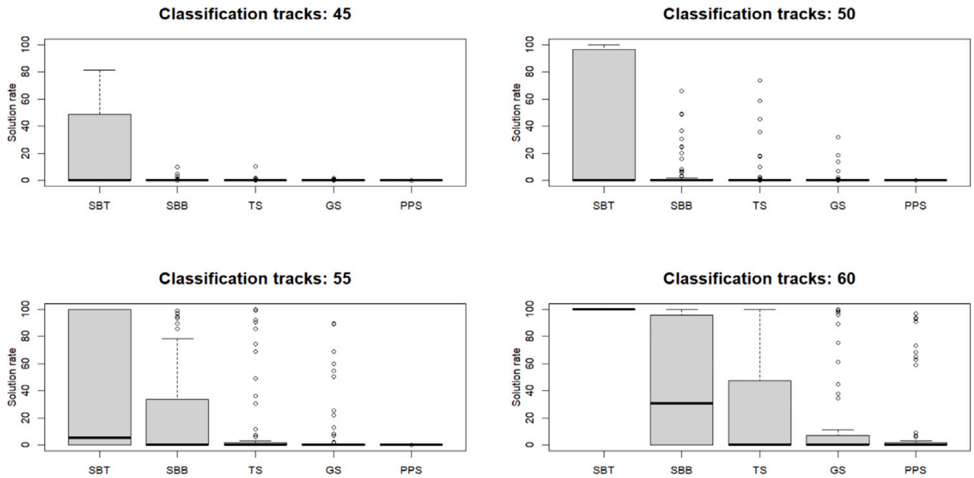

Fig. 10. Solution rates under heavy workload and 45 to 60 classification tracks. Boxplots with medians (black bold line), the box (gray) limited by the lower (25%) and upper (75%) quantile, the whiskers and the outliers (dots).

SBT when 55 tracks are available. With 60 tracks, the median of the solution rates achieved by SBT is 100% meaning it solves the class perfectly. Unable to reach this level, the other strategies follow SBT in the order of SBB, TS, GS, and PPS.

Based on the analysis, it is recommended to use SBT under a heavy workload. However, to develop its power SBT requires a sufficiently large classification yard. Daganzo et al. (1983) examines the relationship between SBT and TS, among other relationships. It is found that SBT requires three humping processes per car, while TS requires only slightly more than 2.5 humping processes per car. The intuitive assumption is therefore that TS is always better than SBT. However, this is not the case. The average number of humping processes per car for triangular sorting based on the position on the classification tracks is derived by the authors. All railcars that are positioned at a headslot, i.e. occupy the first position on a classification track (car 1 on track 1, car 2 on track 2, car 4 on track 3, …) must be shunted exactly twice. All other railcars are shunted exactly three times. This results in an average of 2.5 (or slightly more) humping processes per railcar. However, it is also described that this value increases as the number of outbound trains increases: When the number of outbound trains increases, the number of railcars that are not positioned at a headslot position increases and, therefore, three humping processes are required. Thus, the difference in humping processes per railcar between SBT and TS tends towards zero as the number of outbound trains increases. This is the case under heavy workload conditions.

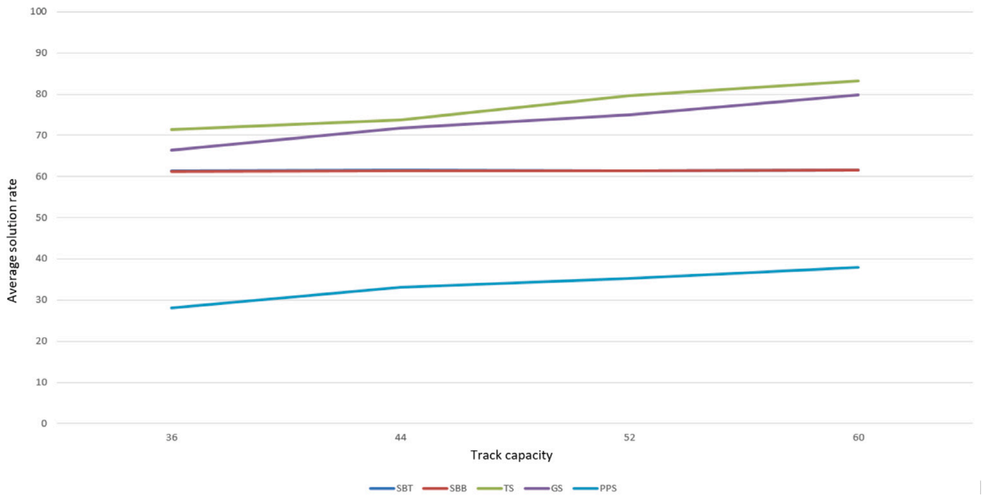

Fig. 11. In-class performance evaluated by track capacity under moderate workload. It should be noted that SBT and SBB produce almost the same curves.

6.4. Impact of the classification track length

To investigate the influence of track length on a strategy's performance, the shunting tasks contained in Data-1 are clustered into four task classes with track capacities of 36, 44, 52, and 60 railcars respectively. Like before, the average-in-class solution rate of a strategy is determined separately for shunting tasks with 10 and with 30 outbound trains to be build. Tasks with 50 outbound trains are not involved.

Shunting under moderate workload. Fig. 11 indicates the diverse behavior of the sorting strategies under moderate workload. The average solution rates depicted in Fig. 11 are calculated over the solution rates of shunting tasks with 10 outbound trains for each track capacity level. Thus, for each track capacity level, the average is calculated on $5 \cdot 3 \cdot 10 \cdot 100 = 15{,}000$ solution rates (5 levels of inbound train numbers, 3 levels of blocks sizes, and 10 levels of track numbers).

With a growing length of classification tracks the average-in-class solution rate improves significantly for TS and GS. In contrast track capacity beyond 36 tracks shows nearly no impact for SBT and SBB. At the same time both strategies perform weaker than TS and GS do. While PPS can take some advantage from longer classification tracks, it is clearly outperformed by the other strategies like before.

The observations made are explained in a straightforward manner. If the track capacity increases, sorting with TS or GS is concentrated on a few tracks and more classification tracks can be used as departing tracks. This increases the number of outbound trains leaving the marshaling yard. If sorting is carried out using SBT or SBB, blocks are distributed to the sorting tracks either according to their affiliation with the outbound trains or according to block numbers. Larger groups of blocks do not arise, so that the average number of trains leaving the marshaling yard does hardly increase when track capacity grows. PPS fails as before, due to a lack of classification tracks. This is hardly counterbalanced by enlarging the lengths of the available tracks.

Shunting under heavy workload. Under heavy workload, the relative performance of the sorting strategies changes again. Corresponding average-in-class solution rates are shown in Fig. 12. Overall, the average-in-class solution rates are below 20% for all sorting strategies which is clearly below the levels reached under moderate workload. The now dominating strategy is SBT which delivers a constant level of performance. Clearly, SBT sorts blocks of railcars according to their affiliation. Since outbound trains are not allowed to tow more than 36 railcars at a time, the strategy never exceeds track capacity. Thus it cannot benefit from longer tracks and behaves invariant against track capacity beyond a value of 36. In contrast, the other strategies can compensate at least partly a limited number of tracks by a growing track length. For SBB, TS, GS and even PPS the average-in-class solution rate improves as track capacity increases.

There appears to be only little yield obtained from higher track capacity in absolute terms. No sorting strategy can transform track length effectively into sorting performance. Hence we conclude that sorting performance of strategies primarily underlies the proportion between workload and the quantity of available classification tracks.

7. Outlook

This work investigates the suitability of sorting strategies for the shunting of trains in marshaling yards. The strategies are based on rules attempting to combine the blocks of inbound trains into outbound trains with as little effort as possible. While doing so they do not take physical restrictions existing in marshaling yards into account. As a remedy we propose a heuristic procedure which decomposes the shunting process into a series of periods such that a rule can be applied without violating the capacity restrictions

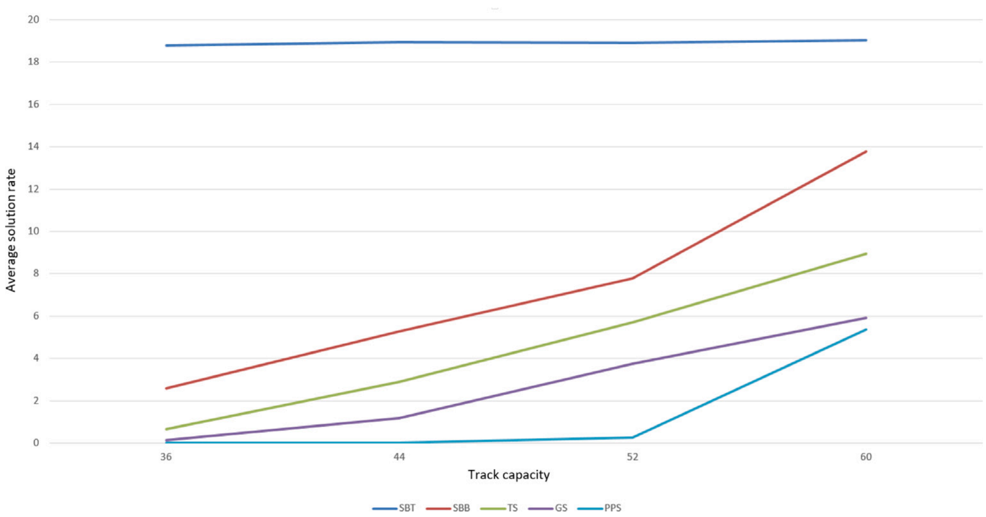

Fig. 12. In-class performance evaluated by track capacity under heavy workload.

coming across. The heuristic and the sorting strategies are tested in a simulation study. A clear picture emerged as to which sorting strategy is best suited in term of solving shunting tasks in a yard with a certain size and workload. The simulation indicates that TS and GS are appropriate for shunting tasks when workload is moderate, meaning that a sufficient number of tracks is available for block classification. When the workloads grows and classification tracks become scarce, SBT turns out as the dominating sorting strategy. In general, it can be said that the number of pullbacks and track utilization represent a trade-off. The number of pullbacks is reduced if more track space is available and vice versa. For example, TS requires a lot of track space, but is accompanied by a reduced number of pullbacks.

A further finding of the study is that sorting strategies often take just little advantage from enlarging track length beyond full train length. In our approach, the classification tracks in a yard are always assumed to have a same length. However, some strategies effect a very unbalanced utilization of the classification tracks, with a few of them running full while others accommodate just a small number of railcars at the same time. Considering yard layouts with classification tracks of unequal length might be subject to future research. By assuming that the receiving tracks are unlimited in number, we have further excluded the receiving area from consideration. In case of a too small receiving area, arriving inbound trains are typically waiting outside of the yard. Hence, deciding whether arriving trains should be pulled in the marshaling yard directly, or not, addresses another subject of future research. Timetables for inbound and outbound trains are only coarsely modeled in this article. In future research, sorting strategies could be adapted to cope with explicit timetables. This leads to a further object of investigation. The model could include the possibility that outbound trains do not leave the marshaling yard at the end of a period, but wait until their scheduled departure time, thus reducing the number of available classification tracks for subsequent periods. Additionally, priority values of railcars represent a promising research subject in order to improve the shunting model.

Declaration of competing interest

There are no financial and personal relationships with other people or organizations.

Appendix A. Formula for f_{tra}

f_{tra} is defined by

$$f_{tra}(r,t,i) = \sum_{w \in \bigcup_{z=1}^{\bar{j}_{i,r}^{TS/GS}} \widehat{W}_{i,z}^{TS/GS} \setminus \bigcup_{s=1}^{t-1} W_{s,i}^{TS/GS,r,out}} n_{w,r}$$

All railcars of an outbound train r are cumulated in period t on track i, which are in all physically existing and scheduled blocks ($\widehat{W}_{i,z}^{TS/GS}$) without already shunted (to other tracks) blocks ($W_{s,i}^{TS/GS,r,out}$). This corresponds to all blocks of an outbound train r that are already on track i and all blocks of the outbound train r that have not yet arrived. For details of determining $\widehat{W}_{i,z}^{TS/GS}$ and $W_{s,i}^{TS/GS,r,out}$ see Zien and Kirschstein (2023).

Appendix B. Distribution of average solution rates for 35 to 60 classification tracks

Representation of the distribution of the solution rates in box plots of the five sorting strategies for moderate workload (10 outbound trains) and the considered marshaling yard consists of 35 to 60 classification tracks.

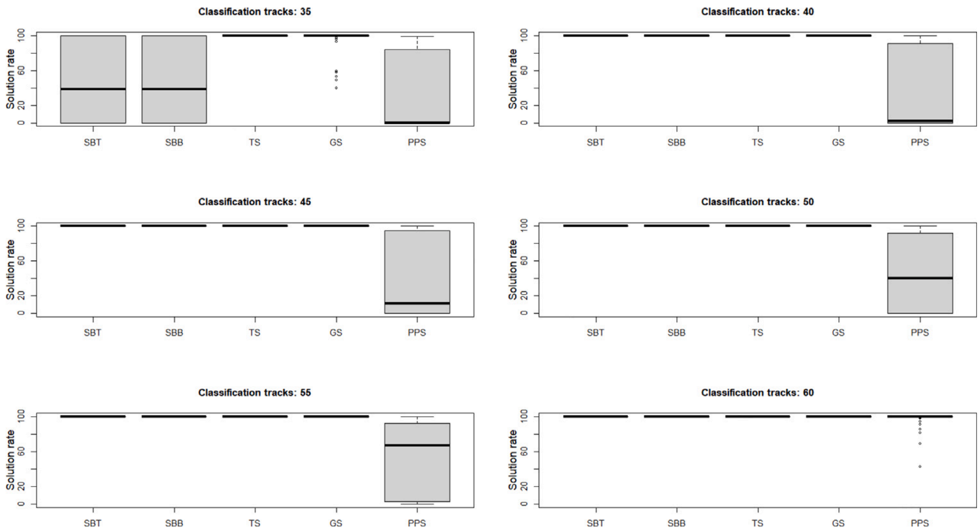

Fig. B.1. Solution rates for 35 to 60 classification tracks under moderate workload (10 outbound trains).

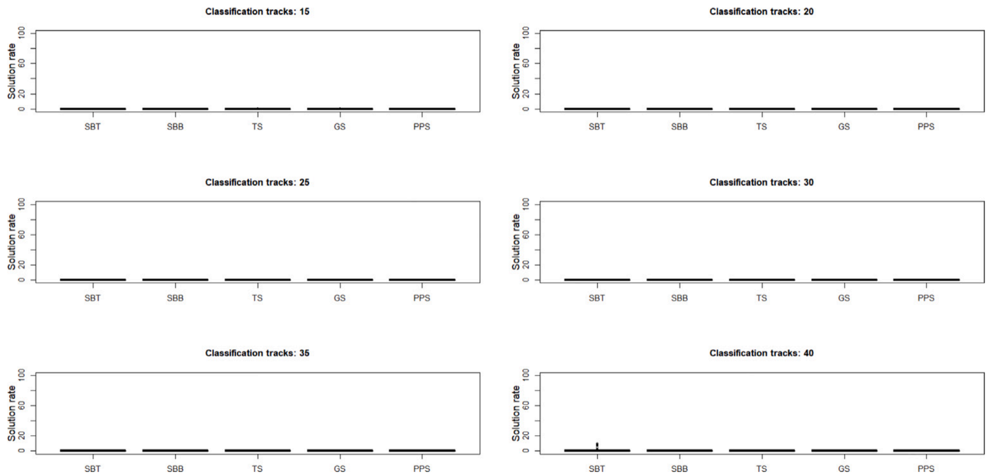

Fig. C.2. Solution rates for 15 to 40 classification tracks under heavy workload (30 outbound trains).

Appendix C. Distribution of average solution rates for 15 to 40 classification tracks

Representation of the distribution of the solution rates in box plots of the five sorting strategies for heavy workload (30 outbound trains) and the considered marshaling yard consists of 15 to 40 classification tracks.

Appendix D. Supplementary data

Supplementary information (Data-1, Data-2) are involved in this article.

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jrtpm.2024.100498.

References

Belošević, I., Ivić, M., 2018. Variable neighborhood search for multistage train classification at strategic planning level. Comput.-Aided Civ. Infrastruct. Eng. 33 (3), 220–242. http://dx.doi.org/10.1111/mice.12304, arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/mice.12304, URL https://onlinelibrary.wiley.com/doi/abs/10.1111/mice.12304.

Bohlin, M., Gestrelius, S., Dahms, F., Mihalák, M., Flier, H., 2016. Optimization methods for multistage freight train formation. Transp. Sci. 50 (3), 823–840. http://dx.doi.org/10.1287/trsc.2014.0580, arXiv:https://doi.org/10.1287/trsc.2014.0580.

Bohlin, M., Hansmann, R., Zimmermann, U.T., 2018. Optimization of railway freight shunting. In: Borndörfer, R., Klug, T., Lamorgese, L., Mannino, C., Reuther, M., Schlechte, T. (Eds.), Handbook of Optimization in the Railway Industry. Springer International Publishing, Cham, pp. 181–212. http://dx.doi.org/10.1007/978-3-319-72153-8_9.

Boysen, N., Emde, S., Fliedner, M., 2016. The basic train makeup problem in shunting yards. OR Spectrum 38 (1), 207–233.

Bundesministerium für Digitales und Verkehr, 2021. Klimaschutz im verkehr - Schienengüterverkehr. URL https://bmdv.bund.de/DE/Themen/Mobilitaet/Klimaschutz-im-Verkehr/Schienengueterverkehr/schienengueterverkehr.html.

Bundesministerium für Verkehr und digitale Infrastruktur, 2017. Masterplan schienengüterverkehr. URL https://bmdv.bund.de/SharedDocs/DE/Publikationen/E/masterplan-schienengueterverkehr.pdf?_blob=publicationFile.

Daganzo, C.F., 1987a. Dynamic blocking for railyards: Part I. Homogeneous traffic. Transp. Res. B 21 (1), 1–27. http://dx.doi.org/10.1016/0191-2615(87)90018-X, URL https://www.sciencedirect.com/science/article/pii/019126158790018X.

Daganzo, C.F., 1987b. Dynamic blocking for railyards: Part II. Heterogeneous traffic. Transp. Res. B 21 (1), 29–40. http://dx.doi.org/10.1016/0191-2615(87)90019-1, URL https://www.sciencedirect.com/science/article/pii/0191261587900191.

Daganzo, C.F., Dowling, R.G., Hall, R.W., 1983. Railroad classification yard throughput: The case of multistage triangular sorting. Transp. Res. A 17 (2), 95–106.

Dahlhaus, E., Horak, P., Miller, M., Ryan, J.F., 2000a. The train marshalling problem. Discrete Appl. Math. 103 (1), 41–54. http://dx.doi.org/10.1016/S0166-218X(99)00219-X, URL https://www.sciencedirect.com/science/article/pii/S0166218X9900219X.

Dahlhaus, E., Manne, F., Miller, M., Ryan, J., 2000b. Algorithms for combinatorial problems related to train marshalling. In: In Proceedings of Awoca 2000, in Hunter Valley. pp. 7–16.

Deleplanque, S., Hosteins, P., Pellegrini, P., Rodriguez, J., 2022. Train management in freight shunting yards: Formalisation and literature review. IET Intell. Transp. Syst. 16 (10), 1286–1305. http://dx.doi.org/10.1049/itr2.12216.

Gatto, M., Maue, J., Mihalák, M., Widmayer, P., 2009. Shunting for dummies: An introductory algorithmic survey. In: Ahuja, R.K., Möhring, R.H., Zaroliagis, C.D. (Eds.), Robust and Online Large-Scale Optimization: Models and Techniques for Transportation Systems. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 310–337, URL https://doi.org/10.1007/978-3-642-05465-5_13.

Gestrelius, S., Aronsson, M., Joborn, M., Bohlin, M., 2017. Towards a comprehensive model for track allocation and roll-time scheduling at marshalling yards. J. Rail Transp. Plan. Manag. 7 (3), 157–170. http://dx.doi.org/10.1016/j.jrtpm.2017.06.002.

Jaehn, F., Rieder, J., Wiehl, A., 2015a. Minimizing delays in a shunting yard. OR Spectr. 37 (2), 407–429. http://dx.doi.org/10.1007/s00291-015-0391-1.

Jaehn, F., Rieder, J., Wiehl, A., 2015b. Single-stage shunting minimizing weighted departure times. Omega 52, 133–141. http://dx.doi.org/10.1016/j.omega.2014.11.001, URL http://www.sciencedirect.com/science/article/pii/S0305048314001406.

Kraft, E., 2002. USPTO 6418854. URL https://www.researchgate.net/publication/352226956_USPTO_6418854.

Kraft, E., 2003. USPTO 6516727. URL https://www.researchgate.net/publication/352227067_USPTO_6516727.

Márton, P., Maue, J., Nunkesser, M., 2009. An improved train classification procedure for the hump yard lausanne triage. In: Clausen, J., Stefano, G.D. (Eds.), 9th Workshop on Algorithmic Approaches for Transportation Modeling, Optimization, and Systems. ATMOS'09, In: OpenAccess Series in Informatics (OASIcs), vol. 12, Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, Dagstuhl, Germany.

Otto, A., Pesch, E., 2017. Operation of shunting yards: train-to-yard assignment problem. J. Bus. Econ. 87 (4), 465–486.

Preis, H., Pollehn, T., Ruf, M., 2023. Optimal resource rescheduling in classification yards considering flexible skill patterns. J. Rail Transp. Plan. Manag. 26, 100390. http://dx.doi.org/10.1016/j.jrtpm.2023.100390, URL https://www.sciencedirect.com/science/article/pii/S2210970623000227.

Raut, S., Sinha, S.K., Khadilkar, H., Salsingikar, S., 2019. A rolling horizon optimisation model for consolidated hump yard operational planning. J. Rail Transp. Plan. Manag. 9, 3–21. http://dx.doi.org/10.1016/j.jrtpm.2018.09.002, URL https://www.sciencedirect.com/science/article/pii/S2210970618300155.

Statistisches Bundesamt, 2022. Rail and inland water transport accounted for one quarter of goods transport performance in 2020.

Statistisches Bundesamt, 2023. Goods transport. URL https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Transport/Goods-Transport/Tables/mode-of-transport-product-division-b.html.

Zhang, H., Lu, G., Zhang, Y., D'Ariano, A., Wu, Y., 2023. Railcar itinerary optimization in railway marshalling yards: A graph neural network based deep reinforcement learning method. http://dx.doi.org/10.2139/ssrn.4673351.

Zien, M., Kirschstein, T., 2021. Greenhouse gas emissions of shunting operations - A simulation study. In: Buscher, U., Lasch, R., Schönberger, J. (Eds.), Logistics Management. Springer International Publishing, Cham, pp. 123–136.

Zien, M., Kirschstein, T., 2023. A rolling horizon approach for shunting operations – An emission oriented simulation study. Clean. Logist. Supply Chain 6, 100093. http://dx.doi.org/10.1016/j.clscn.2023.100093.