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An economic view on rerouting railway wagons in a single wagonload network to avoid congestion

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Abstract

Summary It is expected that in the process of meeting the climate policy goals, more transport will take place by rail. Single wagonload transport plays a crucial role as a direct competitor to road-based transport. The aim of this contribution is an evaluation of capacity correlated effects in a railway wagon routing network.

Methods For this purpose, we developed a mathematical optimisation model. In order to be able to identify the effects and impacts of congestion we created several scenarios and evaluated each of them individually.

Findings By conducting computational experiments we were able to identify various effects and draw conclusions about the impact. This work contributes to the optimisation of the most costefficient short-term rerouting of railway wagons in single wagonload transport.

Keywords Rail freight, Single wagonload transport, Routing model, Rerouting optimisation, Capacity constraints, Network congestion

1 Introduction

Single wagonload transport is a type of transport in which a train consists of railway wagons from different senders and receivers. Groups of wagons from the same sender can have the same receiver [1]. Railway wagons with the same direction are consolidated in nodes to form trains that travel to the next node of the hub and spoke based network. At each node, the railway wagons are reassembled until they reach their destination [2]. This network design requires substantial infrastructure in the nodes and has intensive railway wagon handling. However the existing capacity of the system is better utilised. Due to the higher utilisation of trains, economies of scale occur [3].

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Despite the decommissioning of infrastructure such as sidings, the market share is expected to increase due to its lower impact on the climate compared to other modes of transportation like road transport or aviation [4]. This leads to an increased utilisation of infrastructure. In particular, the nodes in the single wagonload network, the so-called marshalling yards, are to be mentioned as bottlenecks, which are thus highly susceptible to congestion. Thus, research is being carried out to improve the use of existing capacities. Beygang [5] propose an optimisation of shunting operations in marshalling yards by algorithms. In addition to increasing capacity utilisation, single wagonload transport faces further challenges. This concerns both current problems of profitability and reliability as well as the consideration of future developments and planning. A streamlining of processes in single wagonload transport can thus already be initiated in the planning stage in order to reduce overall costs [6]. Innovations such as an integration of intermodal transport into the marshalling yards are taken into account in the long-term planning of the layout and operations [7].

These challenges are aggravated by the fact that it is a system with limited capacity and surrounded by many uncertainties which involves fault management and short-term rerouting of railway wagons.

1.1 Costs in single wagonload transport

Cost optimisation and pricing of transport services are important factors in single wagonload transport. As a study by Guglielminetti et al. indicates, costs are one of the crucial reasons for the general decline in single wagonload transport. In some countries such as the UK, Italy or Spain, single wagonload transport has been discontinued or almost discontinued because the operation is not profitable. Also in Switzerland or Austria, where single wagonload transport is operated, the production costs of up to 50% of the services cannot be covered. Based on the lack of profitability, approaches are developed and potential for cost savings are identified to re-launch single wagonload transport [8]. The introduction of automation components such as digital automatic coupling could have positive effects, as shown in a study by [9].

Various approaches to calculating costs in single wagonload transport are to be found in the literature. For example, experts from the KTI Institute for Transport Sciences and the Research Centre for Transport Development have prepared a study on the full cost calculation [10]. In their analysis, they take into account external monetary as well as non-monetary costs such as energy and climate costs in addition to operational and infrastructure costs. The dominant operator of the German single wagonload transport network with a market share of ~ 95% is the international transport and logistics group DB Cargo AG [11]. In a publicly accessible document of DB Cargo AG detailed price tables are presented for various railway wagon parameters such as distance and weight [12]. However these are the costs that the customer has to pay. There is no public information on the operational costs of the railway wagons and trains. In a study by the European Commission cost structures are taken into account. In this study from 2007 it is stated that the traction costs are 12–15 € per train per km and about 150 € for shunting a railway wagon [13]. Voll stated that costs 6 € per train kilometre and shunting costs of 25 € per railway wagon were accurate according to DB Cargo internal sources [14]. The costs of shunting are about a factor of 6 lower than those of the European Commission study. These large differences show that it is difficult to measure these costs exactly. The publications mentioned above have in common that fixed and variable costs are accumulated and divided into train costs and marshalling yard costs. This is also implemented in this contribution in order to show the effect of short-term diversions.

1.2 Purpose of this contribution

In this contribution we want to focus on the effects of short-term rerouting of railway wagons. Short-term rerouting in this case refers to the alternative routing plan that has to be determined at short notice due to disruptions such as congestion. In order to be able to measure the effects and impacts, we optimise the costs of routing in a network based on the German single wagonload network for different scenarios and compare them with the optimal network, which has an unlimited number of trains and is interference-free. We use some simplifying assumptions in our model to stay within the scope of this paper and to be able to carry out calculations. For example, neither the availability of resources nor time restrictions are currently considered in the model. This procedure allows us to draw conclusions about the various influences. For our approach we use distance based train routing costs and fixed costs for railway wagons.

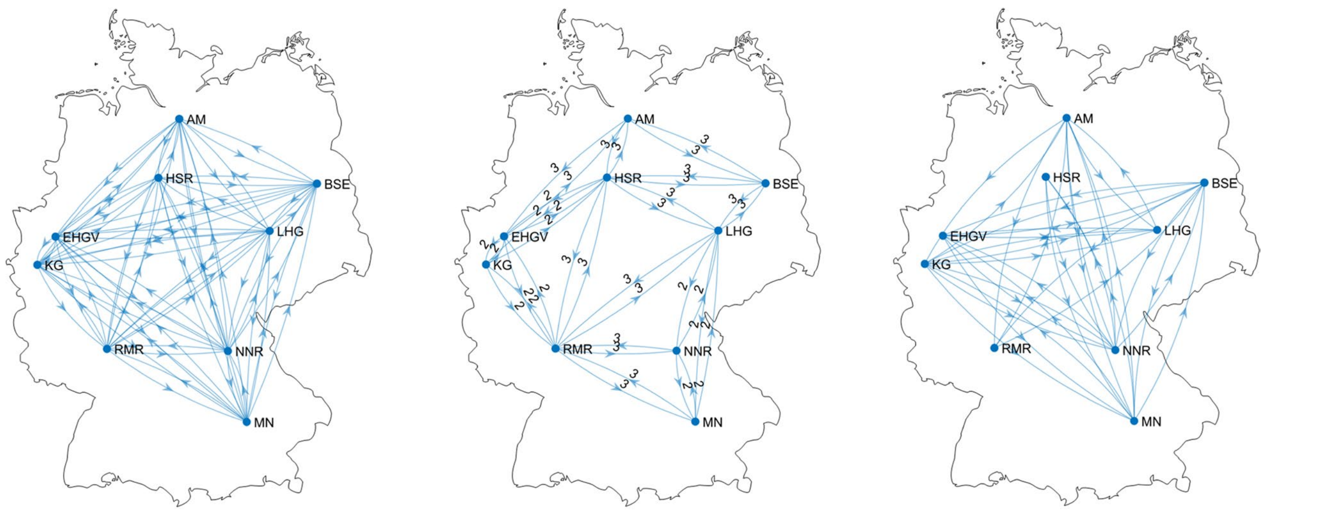
2 Methods

Using a mathematical optimisation model we are able to analyse effects of disturbances (e.g. congestion or closed tracks) in the railroad network. This is primarily depicted by developing multiple scenarios. Each scenario has different constraints regarding the capacity and existence of its arcs.

The model presented below belongs to the class of capacity-constrained routing models. It is based on a model developed by Voll to optimise the total cost of routing [11]. However, the aim is not to determine the costs of a short-term rerouting, but the optimal composition of a transport plan over several days. In contrast, this paper examines the costs for different scenarios with identical other parameters. Therefore several scenarios are developed that extend the existing model. The scenarios are described in detail in chapter 3.

2.1 Development of an arc-related optimisation modell

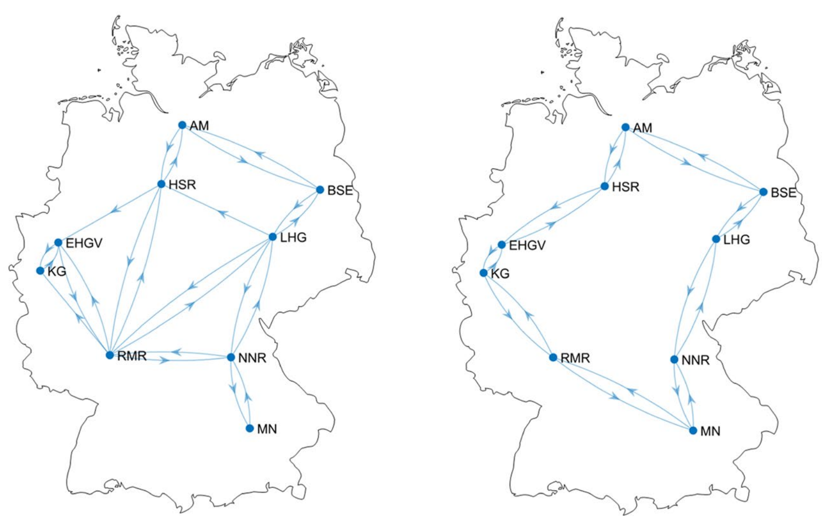
This chapter presents the optimisation model used as the basis for the computational experiments. It is a node and arc based model structured as a hub and spoke network. The nodes represent marshalling yards in the German single wagonload network. The nine large train marshalling yards shown in Fig. 1 are Maschen (AM), Seelze (HSR), Seddin (BSE), Halle (LHG), Hagen-Vorhalle (EHGV), Cologne-Gremberg (KG), Mannheim (RMR), Nuremberg (NNR) and Munich North (MN). Arcs with limited capacity exist between the nodes. Depending on the scenarios presented below different numbers of trains can run over one arc, constraining the optimisation model according to each scenario.



a) Scenario 1: unlimited number of trains on each arc

b) Scenario 2: realistic, maximum number of trains running on each arc is limited to the depiction in fig. above

c) Scenario 3: no connection to direct neighbours, capacity = 3 trains per arc



d) Scenario 4: incident caused network, capacity = 10 trains per arc

e) Scenario 5: circular network, capacity = 10 trains per arc

Fig. 1 Network of each Scenario. The coordinates of the marshalling yards were determined by an artificially created coordinate system that encloses Germany. The relative distances in kilometres thus correspond to the actual distances, whereby the curvature of the earth is neglected

This model minimises the total costs of routing railway wagons in a single wagonload network, which consist of train operation costs and shunting costs in marshalling yards. To obtain the optimal objective function value, the model must therefore find the best composition of train and shunting costs for the total transport volume. In [13] and [14] is stated, that the costs of train operation are primarily dependent on the distance a train has to travel, whereby the shunting costs get accumulated to a value for each shunting process.

First, the sets N, A and K of the optimisation model are defined. The set N contains all marshalling yards i respectively j of the model. Set A defines all connections between marshalling yard i and marshalling yard j. Set K contains all transport orders k and defines their respective start and destination marshalling yard as well as a defined number of cars that cannot be separated on their route through the network. The last mile has been omitted from the problem in order to simplify the model. Then the decision variables x_{ij}^k and y_{ij} are defined. The decision variable x_{ij}^k is the binary routing variable and describes if a transport order k is routed via the arc from marshalling yard i to marshalling yard j. The train operating variable y_{ij} depicts the number of trains running on an arc from marshalling yard i to marshalling yard j and therefore must be an integer. The integer value is bounded by the maximum number of trains allowed on arc i, j.

The objective function

$$\min_{x,y} \sum_{(i,j) \in A} \left[c_{ij} y_{ij} + \sum_{k \in K} r_i n^k x_{ij}^k \right]$$

minimises the distance based train operating costs c_{ij} of the trains y_{ij} running on the arc from i to j as well as the shunting costs r_i incurred in marshalling yard i for the number of railway wagons n^k whose transport order passes through marshalling yard i.

The objective function is subject to several constraints. The first constraint

$$\sum_{i \in N} x_{ji}^k - \sum_{i \in N} x_{ij}^k = D(k,j)$$

is also referred to in the literature as the network flow constraint and ensures that each railway wagon must reach its destination [15]. $D(k,j)$ must be equal to 1 if j is the source of transport order k. It must be -1 if j is the sink of transport order k and 0 in every other case.

Furthermore, a length and a weight constraint are introduced.

$$\sum_{k \in K} l^k x_{ij}^k \leq L_{ij} y_{ij} \quad \text{and}$$
$$\sum_{k \in K} w^k x_{ij}^k \leq W_{ij} y_{ij}$$

These constraints state that the accumulated length l^k of the trains to be formed must never exceed the maximum possible total length L_{ij} of the trains traveling on the arc ij. Equivalently, this applies to the accumulated weight w^k, which must be less than the maximum weight W_{ij} of the trains to be formed.

The last two constraints

$$\sum_{j \in N} y_{ij} \leq V_i \text{ and } \sum_{i \in N} y_{ij} \leq V_j$$

serve as marshalling yard capacity constraints. In the model, the number of arriving trains at marshalling yard j and the number of departing trains at marshalling yard i is limited by the parameter V.

This leads to the following optimisation model:

$$\min_{x,y} \sum_{(i,j) \in A} \left[c_{ij} y_{ij} + \sum_{k \in K} r_i n^k x_{ij}^k \right]$$

$$\begin{aligned}
\text{s. t.} \quad & \sum_{i \in N} x_{ji}^k - \sum_{i \in N} x_{ij}^k = D(k,j) \quad \forall k \in K \quad \forall j \in N \\
& \sum_{k \in K} l^k x_{ij}^k \leq L_{ij} y_{ij} \quad \forall (i,j) \in A \\
& \sum_{k \in K} w^k x_{ij}^k \leq W_{ij} y_{ij} \quad \forall (i,j) \in A \\
& \sum_{j \in N} y_{ij} \leq V_i \quad \forall i \in N \\
& \sum_{i \in N} y_{ij} \leq V_j \quad \forall j \in N \\
& y_{ij} \in \mathbb{N} \quad \forall (i,j) \in A \\
& x_{ij}^k \in \{0,1\} \quad \forall k \in K \quad \forall (i,j) \in A
\end{aligned}$$

3 Creating different scenarios

In this chapter we define five different scenarios to which we apply our model. Thereby, each scenario serves a purpose and is relevant for the analysis below. The nodes are fixed at their specific location in all scenarios, which corresponds to the actual location in the German single wagonload network. The scenarios differ in that the possible arcs are restricted and the number of trains on each arc is limited. In the following the individual scenarios and their use case are presented.

In Scenario 1, as displayed in Fig. 1a), no arc will be blocked and the number of trains on each arc is unlimited. Therefore, it will show us the optimal solution for given optimisation model for each instance. By comparing the objective values of scenarios 2–4 with the optimal solution we are able to make conclusions on the effects and impacts of the scenario specific constraints.

Based on assumptions and publicly available data a simplified image of the German single wagonload network was created in Scenario 2. For example, there are no international connections. Furthermore the distances between the marshalling yards are measured using the Euclidean distance. Arcs are only allowed between certain nodes. For example there are no direct trains between the train marshalling yards Maschen and Munich North. This scenario is intended to approximate reality in the interference-free network. The capacity of the arcs is 3 unless there is a connection that goes directly past a marshalling yard. In this case, the same route is used to a large extent in reality, so that the capacity of the connections concerned is reduced to 2 per arc in order to reflect these circumstances.

To show the effects of detours and long routes, Scenario 3 closes all routes between adjacent marshalling yards (Fig. 1c). It is considered one of the worst negative effects to happen. It is highly uncertain that the network is effected like this in reality. However, evaluating this worst case scenario gives us the possibility to conclude the effects of rerouting over long distances. If the arcs to the nearest nodes are congested or the nodes are in congestion, it is necessary to use a longer route in order to get the transportation order to its predefined destination.

Scenario 4 (Fig. 1d) represents a disturbed image of the approximated German single wagonload network created in Scenario 2. Disruptions can be of different natures, but they do have an impact on operations. In this scenario, more arcs are blocked compared to Scenario 1. On the other hand, the number of running trains and railway wagons cannot be restricted, since the same instance is considered for the comparability of the results. Furthermore in this scenario a few lines can only be used by trains in one direction. E.g. due to track construction work. In reality, depending on the extent of the disruption, it would be possible for trains to use the same track in both directions with implications for the total throughput of the line. Since our model is time-independent, this possibility was explicitly not allowed. Disruptions can be both planned (e.g. construction sites, strikes) and unplanned (e.g. natural events, accidents), with unplanned disruptions requiring rerouting at short notice.

Scenario 5 (Fig. 1e) takes up an idea based on a circular traversal of the network. Each marshalling yard has connections only to its nearest two neighbours. Trains run in both directions so that the network is traversed in a circle clockwise and counterclockwise. In this scenario there are no cross-connections to more distant marshalling yards. Therefore, higher shunting costs are expected here so that the impact of this cost type can be shown. The aim of this scenario is to show how train costs and shunting costs behave, since shorter distances are travelled but more trains have to run to achieve the same transport volume. Furthermore, it is expected that more shunting is necessary.

4 Results

In this chapter the results of our computational experiments will be presented and the framework of our tests will be defined. Although the five scenarios differ in their allowed arcs and their capacities, the optimisation results must be comparable. This is ensured by the framework conditions. A set of parameters remains constant across all experiments. This concerns, for example, the costs. The cost values were determined based on various factors and are an approximation of the values used in practice. These actual values are not publicly available as a company secret, so the decision was determined based on an external analysis. The train operating costs were set to 15 € per train kilometre, while the distance between two marshalling yards is measured by the Euclidean distance. The shunting costs were set to 30 € per railway wagon in the marshalling yards. Another set of parameters, such as the length and weight of the railway wagons and trains, is randomly generated for each instance. The limit values mostly correspond to practice in Germany and can be looked up in [1] and [16]. One instance includes the optimisation of the five scenarios with the same set of (randomly generated) parameters. This ensures comparability between the scenarios for each instance.

We conducted 3 test series for different sets of transport orders. For (i) 100 transport orders, (ii) 150 transport orders and (iii) 200 transport orders, 50 instances each were calculated. This leads to a total of 750 optimisation problems. The instances differ by randomly generated numbers (e.g. length and weight of railway wagons) and the origin and destination of the respective transport orders. The set parameters and ranges are defined as follows:

- Train costs c_{ij}: 15 € per train kilometre
- Shunting costs r_i: 30 € per railway wagon
- Maximum length of train service L_{ij}: 740 m
- Maximum weight of train service W_{ij}: 1600 tons
- Number of arriving resp. departing trains V: 20 trains
- Railway wagon length l^k: 15–30 m
- Railway wagon weight w^k: 20–80 tons
- Number of railway wagons per transport order n^k: 1–5 railway wagons

The optimisation problems were solved by using the solver Gurobi 9.1 (*Gurobi* [17]. The hardware configuration was a Lenovo ThinkPad with a Ryzen 5 Pro CPU and 16 GB of RAM. We set a time limit of 3600 s to find an optimal solution and implemented several valid inequalities to shorten the search room and therefore accelerating the solving process. If no optimal solution was found within time limits, we saved the best objective value found and the remaining gap.

The characteristic values are displayed in Table 1. Most of the problems were solved to optimality within the time limit of 3600 s. However, as the problem grows exponentially with the number of transport orders, in scenario 1 (which is the most complex scenario, because it has the most degrees of freedom) only 11 instances were solved for iii). However, as it can be seen, over all instances the

Table 1 Characteristic values of the optimisation output

# of transport orders	(i) 100 transport orders					(ii) 150 transport orders					(iii) 200 transport orders				
Scenario	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Solved to optimality	50	50	50	50	50	41	49	50	50	50	11	38	49	50	50
Maximum gap	0	0	0	0	0	< 4	< 1	0	0	0	< 3	< 1	< 1	0	0
Mean solution time in [s]	586	33	12	1.7	0.1	1657	258	19	5.2	0.3	3315	1151	209	86	1
Mean number of trains	22.5	23.4	22.7	27.9	26.4	30.7	31.4	30.9	37.6	35.6	39.6	40.5	39.9	47.7	45.3

maximum gap was less than 3% which leads to a good approximation of the minimal costs. As expected the mean solving time increases when creating additional transport orders. In the last column the mean accumulated number of trains is denoted. It can be observed, that doubling the number of transport orders does not lead to a doubling of operating trains. As a result the utilisation of the trains must be more efficient, because on average, the number of railway wagons should be doubled as the mean value of railway wagons per transport order is equal to 3 railway wagons.

The average number of trains operating on each arc for test series (i) is displayed for all five scenarios in Fig. 2. Several observations can be identified on the basis of this illustration. Although all connections are allowed in Scenario 1, closer connections are used more often than longer ones. The connections allowed in Scenario 2 are served by a very similar number of trains in Scenario 1. Although no connections to the closest neighbours are allowed in scenario 3, it can also be observed that trains tend to use short connections over several marshalling yards rather than direct connections. As only a very limited number of connections is allowed in scenario 4, the load on these connections is noticeably higher. In addition, the connections that are only allowed in one direction are frequently used. The balanced utilisation of the routes in Scenario 5 was expected.

The average number of trains operating on each arc was also calculated for test series (ii) and (iii). However, since essentially only the number of trains on the arcs increases on the same scale, it is not displayed.

Figure 3a, b and c show the train operating costs, the shunting costs and the total costs for each scenario of test series (i). The total costs are the sum of the train operating costs and the shunting costs for each instance of the respective scenario, because these two cost types represent all relevant cost types accumulated.

The total costs of Scenario 1 must always be less than or equal to the costs of all other scenarios due to the lack of arc constraints, provided that the optimal solution is found, which is always the case in test series (i). For the train operating and shunting costs, on the other hand, this does not have to apply, as there is a trade-off between the two types of costs.

The similarly low total costs of Scenario 1 for almost all instances are striking. This observation coincides with the similar number of moves on the arcs found in Fig. 2.

It is also evident from the curves that the high total costs of Scenario 3 arise from the additional routes. The shunting costs, on the other hand, are approximately at the level of Scenario 1. With the restriction of paths in Scenario 4, the increased total costs are due to both higher train operating costs and shunting costs. This suggests that railway wagons have to travel longer distances and at the same time pass through a higher number of marshalling yards.

The specifics of Scenario 5 are reflected in the shunting costs. Due to the large number of marshalling yards to be passed, the shunting costs increase and thus the total costs. It is approximately the opposite of Scenario 3, where almost exclusively the train operating costs are responsible for the increase in total costs.

In this case, too, the costs of test series ii) and iii) were determined. They are not shown here, as further observations that can be recognised from them can be better represented in Fig. 4.

Figure 4 shows the average train, shunting and total costs across all instances for all scenarios and all test series. The aim of this presentation is to show the average cost development over the test series.

The figure shows that the costs increase with an increasing number of transport orders. In test series iii), the number of transport orders was doubled compared to test series i). The costs, however, did not double. This is consistent with the observation that the number of trains did not double with double the volume of traffic. Both observations show that in the higher load factor economics of scale show their effect.

5 Discussion

In this paper a model was developed to draw conclusions about the costs of congestion. A model can only represent reality as accurately as its input parameters. Many simplifications and assumptions were made here, which

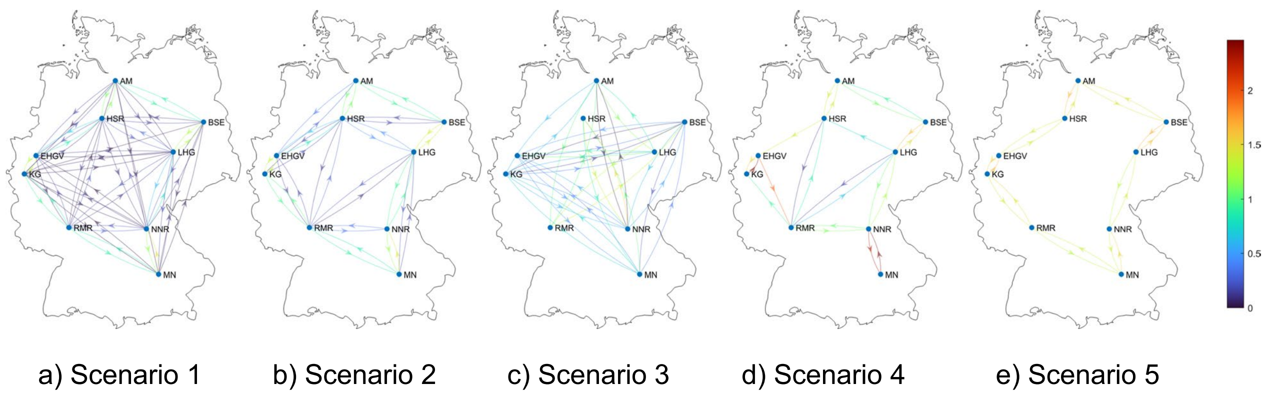


Fig. 2 Colour-weighted mean number of trains on each arc for each Scenario (test series i))

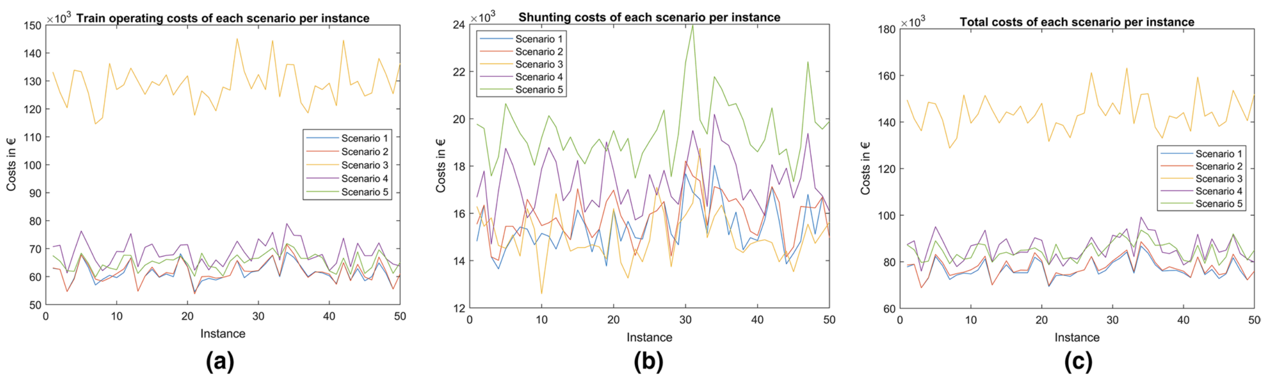


Fig. 3 Train costs, shunting costs and total costs displayed for each computed instance (test series i))

is why the exact costs do not have to correspond to the actual costs incurred. Aside from this, the model allows conclusions to be drawn about reality, since the various scenarios show the dependencies of the cost factors train costs and shunting costs. Short-term rerouting due to congestion, as Scenario 3 shows, has a high impact on train costs due to the longer routes. What is interesting about this scenario, however, is that the shunting costs actually decrease compared to the optimal plan. This means, especially in comparison with Scenario 2, that diversions can help to reduce congestion in marshalling yards. The trade-off is higher costs. These higher costs are confirmed in Scenario 4, where the arcs are congested, e.g. due to disruptions.

As mentioned above, the similarity between the optimal Scenario 1 and the approximated image of the German single wagonload network in Scenario 2 was notable. This suggests that the structure of the German single wagonload network image enables the relevant connections. However, it must be taken into account that some simplifications were made in the creation of the model, so that in reality the costs of the scenarios could deviate more strongly from each other.

Scenario 5 has the advantage of having only 2 arcs in and 2 out. However, although its costs are comparable low it cannot be translated to reality because this model is static, however the environment will be dynamic. In this scenario, railway wagons have to be transported over 4 other marshalling yards in the worst case until they reach their destination. Since a stay in a marshalling yard always takes a long time, the transport time would be considerably longer. Therefore this theoretical scenario is not an option in practice, despite the expected low total costs.

By carrying out computational experiments with different numbers of transport orders, the economics of scale could be proven. It is therefore important to increase the efficiency of the single wagonload network so that the decreasing marginal costs due to the increasing transport volume are not levelled out again by congestion costs.

The evaluation of train costs and shunting costs should also be critically questioned, as they are stated very differently in [13] and [14]. In this work relatively low shunting costs were assumed compared to the above-mentioned up to 150 € per shunting of a railway wagon. A deeper investigation could help to identify a more

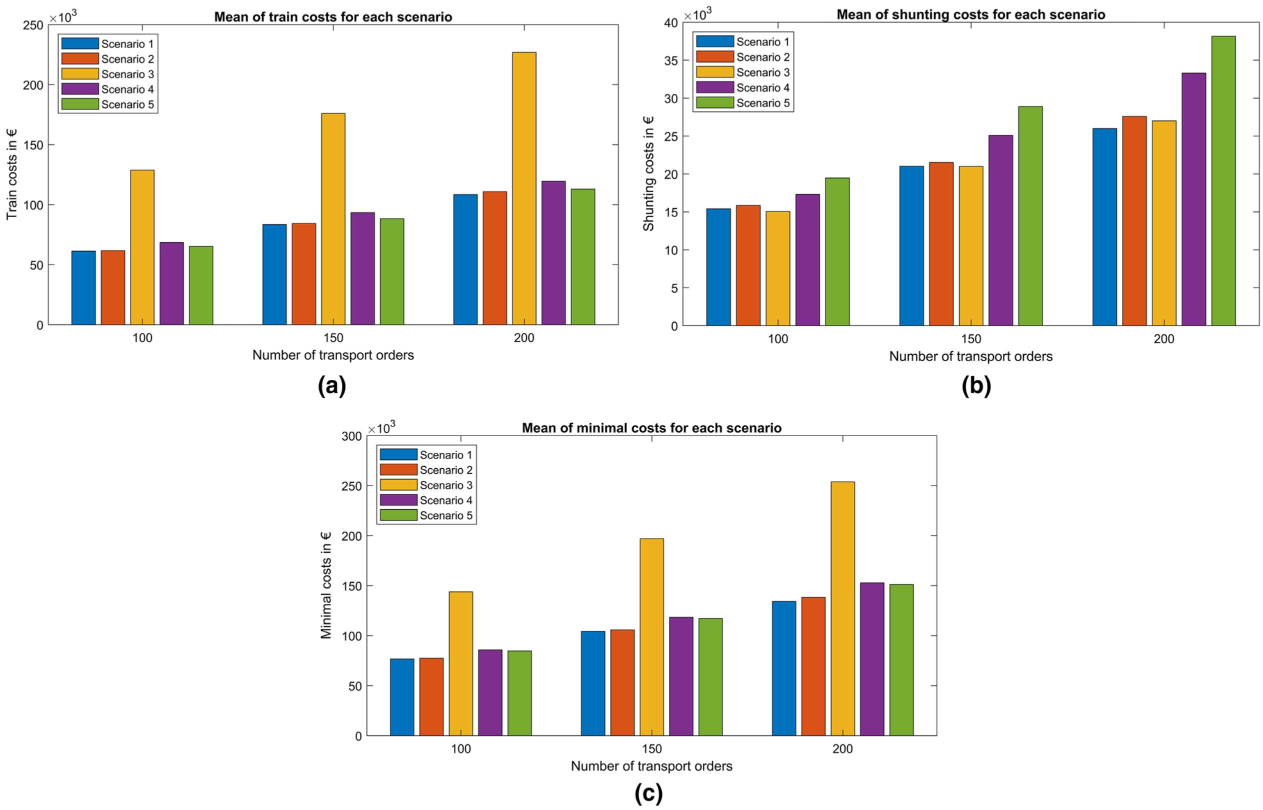


Fig. 4 Mean train, shunting and total costs for each scenario, instance and test series

accurate value. Also the distance between the train formation facilities does not correspond exactly to the linear distance as assumed here in the model.

An investigation of the individual costs only to extend the model is not recommended due to the good representability as accumulated costs. The investigation of an average distance surcharge, on the other hand, could be useful.

6 Conclusion

In conclusion this paper contributes to a better understanding of the impact of railway wagon routing. The analysis of five different scenarios allows to evaluate the impact of short-term rerouting of railway wagons and thus to demonstrate the need for additional capacity to mitigate congestion. This applies in particular against the background of increasing transport volumes. However the model has a few weaknesses. Some assumptions are made and values are generated that do not necessarily match reality exactly. Therefore, only limited conclusions can be drawn about practice. Nevertheless, the results show that the model and the methodology are well suited to be able to recognise influences and effects of congestion in single wagonload transport. To better represent practice with the model, various adjustments should be investigated in future research. Relevant factors are a more accurate data basis and an extension of the model by the time dimension. Regarding the train operation and shunting costs, a breakdown of the individual costs, such as energy, track, wear and tear costs could support the calculation of cost values close to practice without inflating the model.

The model considers the single wagonload network of Germany without international connections. Including other European countries could show further potentials. In addition stochasticity of processes could be considered. For example disruptions can occur with a certain probability and cause line closures, or a marshalling yard could be closed for a certain period of time with a certain probability due to congestion. Single wagonload transportation faces challenges with far-reaching implications for the future of single wagonload transport. The developments could be considered in further research.

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Author contributions
MK researched the basics, formulated the model, designed the scenarios, conducted and evaluated the experiments and drafted the manuscript. DH assisted in the development of the model. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare they have no competing interests.

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