The Wagon Assignment Policy problem: Policy Comparison on the Wagon Fleet optimization.

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SHORT SUMMARY

By 2050, Europe hopes to nearly double the freight traffic train in order to achieve carbon neutrality. One of the challenges that multimodal freight transport will face is related to optimizing the high costs associated with the management of rolling stock. In this context, we study an integration of the maintenance constraint for the Rolling Stock Problem, defined as the Wagon Assignment Policy problem, focusing on how to optimize the wagon fleet management with a particular focus on the shunting operations. For this reason, an event-based simulation approach has been developed in order to understand the long-term impact of multiple policies. Results show that the criteria for choosing which wagons to assign to a departing train greatly impacts the KPIs regarding fleet management. We show that different criteria for the Wagon Assignment Policy can reduce the number of rolling stock needed for the fulfillment of the freight services.

Keywords: Freight trains operation, Mileage-based maintenance, Shunting operations, Rolling stock problem, Wagon maintenance.

1. INTRODUCTION

By 2050, Europe has declared that its goal is to reach carbon neutrality, which means having a balance between the production of carbon and absorbing it from the atmosphere in carbon sinks. Regarding the transportation sector, we saw that by 2016 almost 51% of goods were transported by road, compared to the 12% transported by rail. Moreover, in 2020 freight rail transportation managed to reach the carbon footprint of 7800 Tonne of CO2 per Tonne/km, versus the 92066 Tonne of CO2 per Tonne/km of road transport (Greene, 2020). Being the transport mode with the lowest emission, Europe expect, in order to reach their goals while keeping up with the demands of goods, an increase of almost double the freight traffic by that year. Therefore, one of the challenges facing freight transport in the next years is related to the optimization of the management of freight operations. In this context, the management of rolling stock, and in particular the optimization of shunting operations due to creating new compositions of the outbound trains' wagons and to wagons maintenance, will play a key role in allowing this transformation and reducing the cost framework of railway companies. Usually, the shunting optimization problem is usually divided into two interrelated sub-problems, the Rolling Stock Problem (RSP) and the Train Unit Shunting Problem (TUSP).

Literature Review

The Rolling Stock Problem (RSP) deals with the planning optimization of the rolling stock, which consists of assigning a time of service to each wagon in order to best manage wagon and/or train units and in turn reduce costs to supply the services or to cover the demand. This problem is usually divided into two sub-problems, the Rolling Stock Circulation (RSC), which deals with the assignment of locomotives and carriages to the timetable services, and the Rolling Stock Rostering (RSR), which focuses on the assignment of a roster to each individual train unit (Cadarso & Marín, 2012).

The Train Unit Shunting Problem deals with the management of the shunting yard in order to optimize the operations. For (Kroon, Lentink, & Schrijver, 2008), the process of parking unused rolling stock units together with several related processes inside a yard is defined as shunting, with the corresponding planning problem defined as the Train Unit Shunting Problem. (Winter, 1999) theoretically extends the TUSP approach considering length restrictions for the trains and mixed arrival and departures, discussing also an application for the bus depot.

The maintenance of rolling stocks impact both in economical terms and unavailability of the fleet, and their integration with both the RSP and TUSP has been studied as well in the literature. (Herr et al., 2020) solve the RSP and the scheduling of maintenance for passenger trains. (Giacco, Carillo, D'Ariano, Pacciarelli, & Marín, 2014) developed an integration of these problems, solving the RSP first and subsequently the TUSP, and finally integrating the Maintenance Scheduling Problem, realizing that this approach could create situations where additional operations are needed to schedule a rolling stock for maintenance, resulting in more costs for companies. Despite all the studies found, to the best of our knowledge, few studies have been conducted on the analysis of the RSP problem with mileage-maintenance constraints, which are constraints that consider the mileage performed by a specific rolling stock unit for maintenance planning purposes.

Proposed Methodology

The integration of this maintenance constraint, the RSR, and the delay management has been studied (Bigi, Bosi, Pineda-Jaramillo J., Viti, & D'Ariano, 2022) with the definition of the Wagon Assignment Policy (WAP) problem, a RSP subproblem that aims to analyze the criteria to use for assigning rolling stock to services. This impacts directly the TUSP problem since the output provided by this model is the rolling stock that must be fitted inside a departing train. The WAP problem increases in complexity and decreases in solution quality when other factors such as the heterogeneity of a typical wagon freight fleet are included, since that variables in a NP-Hard problem are increasing (Dahlhaus, Horak, Miller, & Ryan, 2000), being itself part of the RSP problem. Therefore, this study presents a comparison between multiple WAPs, respectively Min, Average Long-Short, Reserving, and NCLD policies, with their respective benchmark. This comparison has been achieved by using as input a real timetable used by the Luxembourg National Railway Company. This study highlights how the use of different criteria for assigning the rolling stock, and therefore different WAPs, can impact in the long term the wagon fleet, while analyzing the pros and cons of different criteria for the assignment of wagons.

2. METHODOLOGY

Given a train T, a route that the train has to perform R and a list of wagon $W = W_T \cup W_D$, respectively the wagons inside the trains and the wagons inside the shunting yard, we define $W_S \subseteq W_T$ as the wagons in the train that requires shunting operations.
To each wagon $w \in W$ are associated: an actual mileage a_w, a max mileage m_w before maintenance, after which the wagon has to be mandatory sent to maintenance for a fixed time τ, and a wagon type $t_w \in [1,2]$, corresponding respectively to the type *simple* or *double*. These two wagon types are a common classification for freight wagons, divided by tare, but it can easily be extended to the multiple types of rolling stocks existing in the freight industry. When $a_w \geq m_w$ for a wagon w, the wagon is then sent to maintenance and becomes available again with $a_w = 0$ after τ days. For this study, this is our definition of maintenance constraint.

Policies

The objective of these policies is to allocate wagons w to fulfill the demand of a departing train based on different criteria, choosing among those available parked on the shunting yard. The selected wagon will belong to the appropriate set S_{T_i}, associated with the train T, defined as $S_{T_i} = \{w \in W \mid m_w \geq R + a_w, t_w = t_i\}$, with t_i as the type of the wagon at position i that must be shunted due to the composition of the departing train or the need for maintenance. Moreover, we define *short* distance services as trips performed with a value less than the 25$^{\text{th}}$ percentile of the maximum distance that can be covered in the instance, respectively; and we define *long* distance services as the trips performed with a value higher than the 25$^{\text{th}}$ percentile.

To solve the WAP problem, we identified four different policies to be tested: Min, Reserving, the Average Long-Short (AVG L-S), and NCLD.

- The Min policy aims to allocate wagons w to fulfill the demand of a departing train based on the minimum mileage among those available parked on the shunting yard.
- The Reserving policy aims to assign wagons $w \in W_D$ based on their *degree of use*, defined as: $\beta_w = R/(m_i - a_i)$. When a train requires shunting operations, we verify if the wagons will be assigned to a *short* distance service. Therefore, the wagon with the $\min \beta_w$ is assigned, otherwise, the wagon with the $\max \beta_w$ is assigned. This is done in order to maximize the short services that can be fulfilled in the instance.
- The AVG L-S policy aims to keep a balance between short and long trips performed by rolling stock. This is done by computing the *degree of unbalanceness* for each wagon in the shunting yard: $\gamma_w = \#long - \#short$. If a service is a *long* distance, then the wagon with the $\max \gamma_w$ is assigned, otherwise, the wagon with the $\min \gamma_w$ is assigned. The aim of this criterion is to keep an average between long and short trips made by the rolling stocks.
- The miNimum distanCe simiLar Deadline (NCLD) policy focuses on fitting wagons with homogeneous mileage inside a train. This is performed by computing the average *index of use* of the wagon that do not require shunting as $A = [\sum_{i \in W_T \setminus W_S} (a_i + R)/m_i]/n$, with n as

the number of wagons in the train. Then, $\forall w \in W_D$, we compute the *degree of similarity* as $\delta_w = |(a_i + R)/m_i - A|$. Finally, the wagon inside the shunting yard with the $\min \delta_w$ is chosen. The idea behind this criteria is to keep the average a_i of the wagons inside the train as close as possible.

To compare our policies, we developed a benchmark, or no - maintenance scenario. This has been developed running each WAP model on the same instance relaxing the maintenance constraints, resulting in a modified RSR, so that no maintenance was needed throughout the simulation. This is an unrealistic situation that, nonetheless, provides a good Lower Bound for our instance.

Data

In order to highlight the different behavior of the policies, we conducted a quantitative analysis based on the timetable provided by the Luxembourg Railway Company for the freight trains operations for the period 2019 - 2021. From this timetable, the year 2020 is extracted and expanded for 20 years in order to assess the long-term impact of the choices of these criteria by obtaining a timetable for 2020 - 2040. After the data expansion, the traffic of freight trains incoming and departing from the Bettembourg train station in Luxembourg, along with all the operations carried out there on freight trains, including maintenance, is simulated. Besides, all the policies were simulated with the timetable in order to compare them, with routes that each train must cover varying between 200 and 1000 km with a total of 28 trains in the system and 1600 wagons divided between *SIMPLE* or *DOUBLE* according to the distribution of wagons extracted from the timetable. The *short* distance threshold has been set as 461.5 km, covering around 45% of the services. Regarding the costs, each shunting operation performed costs 350 euros per operation and can only be performed if the shunting yard is not busy performing other shunting operations. For these simulations, a FIFO queue policy is applied in case multiple trains are waiting for shunting operations, and a shunting yard can only shunt one train at a time.
In relation to the maintenance constraint, we set $m_w = 250000$ km, and a wagon requires 3 days to become available again within the system with $a_w = 0$. When a wagon requires maintenance, it is considered that an additional shunting is sent from the shunting yard to the maintenance depot, which increases the overall number of shunting operations performed. The choice of the mileage-based approach has been considered to be a suitable solution for this simulation approach, as a condition-based approach could not be implemented for now and is one of the most effective maintenance approaches for the railway industry (S.Stazzone, 2021).

3. RESULTS AND DISCUSSION

	NCLD	Min	Reserving	AVG L-S
	Benchmark			
Shunting Ops.	16434	16434	16434	16434
Wagons Used	276	1199	1198	269
	Operations on each wagon			
Mean	88.68	20.29	20.29	87.46
Median	71	13	13	30
Variance	75.78	21.55	21.55	143.59
	Annual Miles Performed per wagon (km)			
Mean	27717.93	3536.2	3536.2	26145.17
Median	21782.3	1320.9	1320.9	7774.3
Variance	17272.87	6209.33	6209.33	41142.57
	With Maintenance Constraint			
Shunting Ops.	18427	16850	17050	18514
Wagons Used	1385	1335	1338	791
	Operations on each wagon			
Mean	19.36	19.23	19.25	34.06
Median	10	12	13	10
Variance	38.73	21.74	21.55	86.24
	Annual Miles Performed per wagon (km)			
Mean	17458	15509.34	15877.81	30344.72
Median	12490.8	12709.3	12772.5	12456.5
Variance	33683.83	17310.18	18170.06	55399.37
	Comparison			
Shunting Ops.	11%	2%	4%	11%
Wagons Used	80%	10%	10%	66%
Annual Miles Performed	37%	77%	78%	14%

Table 1: Performance comparison between the policies and their respective benchmark.

Table 1 presents the data on fleet management for each policy.

Benchmark

As seen in the Benchmark, although the same number of shunting operations has been performed in each simulation, this is not valid for the same number of used wagons. This occurs because NCLD tends to use wagons that are already used, AVG L-S exploits the unbalanceness of the wagons, forcing the choice on a limited pool of wagons, while the other policies' criteria push them to use more and different rolling stock. Furthermore, the higher mean, median, variance of both NCLD and AVG L-S for shunting operations show their better management in terms of wagon usage for the no-maintenance scenario. This can also be seen in the data for the annual miles performed for these two policies, which are much higher compared to Min and Reserving. Moreover, NCLD reflects a more compact and resilient behavior showing a lower variance when looking at both KPIs. This is desirable in order not to have some overused rolling stocks.

Maintenance Constraint

When including the maintenance constraint, important changes occur. The number of shunting operations performed in each scenario increases from 2% up to 11% due to the maintenance constraint. This increase is caused and can be directly referred to maintenance operations. Interestingly, while NCLD, Min, and Reserving present similar data in terms of shunting operations performed on each wagon, AVG L-S presents almost double the mean and variance with a similar median. This, together with higher values in terms of miles performed, highlights better exploitation of the fleet from this last policy when including the maintenance constraint. This occurs despite an increase in the number of shunting operations performed for maintenance reasons. The number of used wagons increases due to the unavailability of the fleet caused by the maintenance constraint, forcing the policies to choose wagons that are not the optimal choice for their criteria. It is important to emphasize how much this maintenance constraint can affect in terms of wagons used, which can increase up to 80% more for the NCLD policy and 66% for AVG L-S, bringing the distribution of shunting operations on each wagon way closer to the mean in comparison to the Benchmark scenario, creating a more evenly distributed scenario, increasing the number of wagons used.

From 1 it can be stated that more shunting operations due to maintenance constraints and higher annual mileage for each wagon can be a symptom of better fleet management, at least for this preliminary study. On the other hand, is not desirable to have asymmetry for the wagon fleet usage as the one that can be seen in AVG L-S for both the benchmark and the maintenance scenarios.

4. CONCLUSIONS

This study analyzes a comparison for the integration of maintenance constraints in the RSP problem, defined as the WAP problem. The integration of a maintenance constraint for wagons shows that the quality of the solution decreases in comparison to the benchmark problem, but it provides more precise data on the long-term impact of these constraints. Although this constraint proved to have a great impact in terms of Fleet Usage, this methodology could become a useful tool for the railway managers in order to improve their fleet management, given the low cost of its implementation.

Possible future developments could be creating new policies, understanding how the WAPs can be used as a new tool to improve the overall freight management, expanding the demand in order to adhere to trends of the freight railway transport, implementing forecasting demand by introducing information on demand cyclicity, which can greatly improve the efficiency of the policies. Moreover, a combination of policies could be studied, by analyzing them from different perspectives, such as a cost analysis. Finally, a lease constraint could be introduced into the WAP problem in order to assess fleet usage and reduce the pool of wagons owned, thus reducing the number of wagons needed to find a feasible solution.

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