A new approach to speed optimization of empty platform wagons in the Southeast region of Brazil

Uma nova abordagem para a otimização de velocidade de vagões de plataforma vazios na região Sudeste Do Brasil

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Eduardo Batista Jenz Carneiro
Formação acadêmica mais alta: Mestrado
Instituição de atuação atual: Instituto Militar de Engenharia
Endereço completo (pode ser institucional ou pessoal, como preferir)
Nair Furtado de Souza, 245, apto 301, Jardim Laranjeiras
36033-190 – Juiz de Fora - MG
E-mail: eduardo.jenz@engenharia.ufjf.br

Paulo Afonso Lopes da Silva
Formação acadêmica mais alta: Doutorado
Instituição de atuação atual: Instituto Militar de Engenharia
Endereço completo (pode ser institucional ou pessoal, como preferir)
Boulevard Vinte e Oito de Setembro, 226, cob. 07, Vila Isabel
20551-031 - Rio de Janeiro - RJ
E-mail: pauloafonsolopes@uol.com.br

Luiz Antônio Silveira Lopes
Formação acadêmica mais alta: Doutorado
Instituição de atuação atual: Instituto Militar de Engenharia
Endereço completo (pode ser institucional ou pessoal, como preferir)
Lauro Muller, 128, apto 1002, Urca
22290-160 – Rio de Janeiro - RJ
E-mail: laslopes@uol.com.br

ABSTRACT
Matching the demand for rail freight transportation depends on the railroad network structure and the availability of the rolling stock, locomotives and wagons. The distribution of wagons optimization helps reduce transportation costs, and the efficient allocation of assets is essential for rail competitiveness with other means of transportation. The present study aims to develop a mathematical model for optimizing the allocation of wagons and minimizing the distribution cost, adopted as empty transit time. The model also calculates the empty transit time of wagons according to demand distribution, and reduces the necessity for rail freight assets, because it also minimizes the wagon cycle. An algorithm was developed from the characteristics related to the distribution of freight wagons, using planned cycles adjusted by the demand distribution, and mathematical modeling was performed, applying integer linear programming to minimize the empty wagon transit time in a railway company. As a result, a weighted and optimized cycle was obtained to perform the sizing of wagons and meet the transportation plan, as well as minimizing the transit time between unloading and loading of goods. The new model presents a contribution to the operation, because, in addition to directing the optimal
distribution of the assets using an integer linear programming algorithm, it also allows the planned wagon cycle adequacy, according to the demand of the respective period.

**Keywords**: Logistics, railroad, wagon allocation, optimization, routing.

**RESUMO**
O atendimento da demanda para transporte de carga nas ferrovias depende da estrutura da malha e da disponibilidade dos ativos de material rodante, locomotivas e vagões. O processo de distribuição dos vagões de modo otimizado contribui para reduzir o custo do transporte, e essa eficiência de alocação dos ativos é essencial para competitividade das ferrovias com outros modos de transporte. O objetivo do presente estudo foi desenvolver um modelo matemático para otimizar a alocacao de vagões, minimizando o custo da distribuição, adotado como tempo de trânsito vazio. O modelo ainda calcula o tempo de trânsito vazio dos vagões de acordo com a distribuição de demanda, e reduz a necessidade de ativos para o transporte ferroviário de carga, porque também minimiza o ciclo dos vagões. Esse algoritmo foi desenvolvido a partir das características relacionadas à distribuição de vagões de carga, utilizando ciclos planejados ajustados pela distribuição da demanda. Para isso, foi realizada uma modelagem matemática, aplicando um modelo de programação linear inteira para minimizar o tempo de trânsito do vagão vazio em uma empresa de transporte ferroviário. Como resultado, foi obtido um ciclo ponderado e otimizado para realizar o dimensionamento de vagões e atender o plano de transporte, além da minimização do tempo de trânsito entre descarga e carga.

**Palavras-chave**: Logística, ferrovia, alocação de vagões, otimização, roteamento.

**1 INTRODUCTION**

Rail systems are loosely flexible and have operations such as overtaking and intersections that are more complex than other means of transportation, such as waterway or road. This feature makes it essential to apply planning and scheduling optimization in the railway operation and maintenance to enable leverage recovery in the railway network (FIORONI, 2008).

The rail system operations are relatively slow compared to other alternatives of transportation, so any failure to plan or move assets can impact responsiveness and safety. This aspect may directly reflect on customers' quality perception of the transportation service or undermine the possibility of rail transportation regarding other alternatives available.

Cargo transportation on Brazilian railways has reached a record of 569.8 million usable tons in 2018, an increase of 125.2% in volume since 1997 when the concessions began (ANTF, 2018). This increase has boosted the necessity to develop ways to increase the productivity and efficiency of the assets and the rail network.

The fixed cost in this type of transportation is considerably higher than the variable costs (WANKE; FLEURY, 2006). Therefore, the rail mode needs massive investment in infrastructure, superstructure, and rolling stock, because the cost of road construction is high. As a recent example of reference found for railway work cost, we can mention the cost of approximately Real 1 million per kilometer for the construction of the superstructure and infrastructure of the grid that connects the...
north-south railway with the branch called Transnordestina, located in the northeast of Brazil (VALEC, 2012). Therefore, the transportation system must be productive, to reduce the necessity for assets allocated to carry out cargo transportation and to mitigate the construction of new railroads before the road system saturation. Besides, undercarriage investment can be minimized without hampering the demand and growth of the railway dealership.

Inefficient wagon allocation can be considered as one of the most serious errors in railway logistics due to planning failure (CALADO et al., 2017). To mitigate this problem, planning tools contribute to decision support and predictability in asset allocation, which is crucial for customers' production and sales schedules. The level of service is characterized by speed of service, honor to commitments made, and cost about transportation. This is why it is important to optimize the way the fleet is distributed and make it possible to quickly respond to the customer’s needs (KARSTEN; ROPKE; PISINGER, 2018).

Although there are monthly planned volumes, the production variability, and the need to transfer stocks to distribution centers or the end customer's purchase orders lead to the necessity of daily adjustments of freight wagon offers. This happens because rail transportation is not as agile as the road one, and this relative slowness is compensated by the volume supported by railway compositions, which makes the cost of transportation per ton lower than that of road transportation.

The main contribution of this paper is to present an algorithm to optimize the distribution of empty wagons from unloading terminals to cargo terminals. The new approach is evidenced by the identification of the best distribution of assets to meet the planned transportation volume, considering the demand for origin and destination. Thus, the empty transit time of the wagons is estimated between the unloading and loading terminals to which they are assigned from the requested volume and serves as input to calculate the wagon cycle in the respective period. The parameters obtained are used to dimension the number of assets required to perform the requested transportation.

2 RESEARCH QUESTIONS AND METHODS

GOMES et al., 2019 developed an application of computational tool in the optimization and mitigation of costs in routing of charge transport logistics. This study was carried out with a focus on the road freight transport mode, with the objective of defining vehicle routes, given the importance of logistical transport planning and the benefits that the routing solution provides for companies that work with physical distribution.

Some authors, such as FRANCESCHETTI et al. (2018), developed models related to what will be presented in this study, focusing on the distribution of assets to terminals. They elaborated on a shorter path model for the starting time and speed optimization problem. They also considered the
environmental factor and stated that parking at customers' terminals to wait for cargo could be a good option for reducing pollutant gas emissions, as terminals do not need to be attached to locomotives.

GHILAS et al. (2018) developed an algorithm to optimize the distribution of cargo vehicles through routing, which would also capture opportunities for passenger transportation on some stretches to increase profit and to route loads to existing lines, minimizing system congestion. Calado et al. (2017) observed, as a result of their model, the opportunity to increase cargo volume by optimally scheduling wagons, as well as the possibility to set targets for some variables such as travel timing, number of wagons retained for maintenance, and the necessity of fleet increasing, considering the transportation program and existing operating assumptions, such as wagon cycle, and terminal capacity.

Bojović (2002), in turn, obtained, from his model implemented on MATLAB, the behavior of wagons of only one type, over a seven-day horizon. It has recorded the number of wagons updated at the end of each day at each station, and obtained unitary costs for empty wagons, queued wagons, estimated travel time, and also measured travel time variance for all destinations. His work made it possible to estimate the cost of some stages such as the empty wagon trip, the loaded wagon trip, and the lack of wagon to meet the demand.

The movement of general cargo vehicles may occur on unitary trains, which are solely formed for the carriage of one type of product and have no intermediate stops for other wagons attachment or removal of. There is also the possibility, more frequent, of being carried on general cargo rail trains, with intermediate stops in courtyards of their itinerary for attachments and withdrawals of vehicles, according to the respective destinations of the wagons or locomotives, which allows the formation of lots per destination for minimizing transportation costs (DOS SANTOS et al., 2018).

The rail system is less flexible and has more complex operations, such as overtaking and crossing, than other means of transportation, such as the waterway or road. These characteristics make essential the application of optimization in the planning and scheduling of operation and maintenance, to leverage the productivity in the rail network (FIORONI, 2008).

Thus, the objective of the present study was to develop a mathematical model as a tool to optimize the allocation of wagons, with directions for loading at terminals close to unloading, to minimize the cost of distribution, adopted as empty transit time. Also, the model calculates empty transit time and reduces the necessity for rail freight assets because it also minimizes the cycle of wagons.

For the model construction, linear programming was used, because it allows solutions of maximization or minimization, in the objective function, subject to restrictions, translated into
equations or inequalities. Besides, the simplex method, applied in this study also presents the non-negativity restriction for all variables.

The proposed optimization model is related to the problem of defining how empty wagons should be redistributed to cargo terminals from the discharge terminals considering the demand, with a focus on reducing empty vehicle time, which, considered the cost for the proposed study. The following steps are the answer to this problem, considering some assumptions for train times, origin, and destination, for to minimize the empty wagon time:

**Step 1:** A tool has been developed on Visual Basic Application (VBA), whose output is the summary of the train grid, considering all the times of circulation and permanence in each courtyard. The obtained results were structured in a matrix on Microsoft Excel, which facilitated the insertion of the data in the model. This step is crucial to enable the identification of the train sequence in the wagon route to the cargo terminal and to ensure the shortest global transit time in the empty condition.

**Step 2:** The monthly transportation plan, characterized by the distribution of the demand among the loading and unloading terminals, and the available resources to move the wagons, has entries to calculate the demands and offers of loaded and empty wagons at the terminals.

**Step 3:** The processing capacity of the loading and unloading terminals, in addition to the commercially established minimum lots, were constraints considered in the construction of the model.

**Step 4:** Figure 1 illustrates the flux of decisions made by the model for the of the empty wagon distribution. The sequence of activities among completion of unloading, wagon circulation, loading, and movement of the wagon loaded to return to unloading characterize the wagon cycle concept.

The optimization of the empty transit time to obtain a new planned cycle is illustrated in figure 2, which compares the industrial practice scenario and the solution developed in this study. In industrial planning practice, the wagon cycle time is calculated by considering the return after unloading to the
previous cargo terminal so that the wagon is always processed at the same terminals. In the developed solution, the optimization directs the empty wagon to the cargo terminals, which reduces the empty traffic stage, and this allows the obtainment of the planned cycles on demand and per period. The routes highlighted in figure 2 illustrate the optimization performed by the model: the wagons that were unloaded at terminal 1 circulate to terminal 5; empty wagons from terminal 5 run to terminal 2; terminal 2 empty wagons circulate to terminal 1, and terminal wagons carrying terminal 3 to terminal 4 return empty to terminal 3:

Fig. 2: Comparison of scenarios for the distribution of empty wagons

In this context, the development of a tool that uses optimization concepts allows a better and more agile distribution of empty wagons, considering routes with shorter transit times, for reuse of assets, and more productive use during empty traffic. This happens because the model considers all the available empty wagons, the demands of each cargo terminal, and optimizes overall transit time. Also, according to volume per terminal and customer, the model also contributes to wagon monthly dimensioning, and optimizing the distribution that the demand requires, because it calculates the empty transit time based on the demand distribution. The new cycle, considering the calculated empty transit time, is used to scale the necessity of assets.

**Step 5:** The model, solved by Integer Linear Programming, was implemented on LINGO software.
3 FINDINGS AND DISCUSSION

The estimate of empty transit time was obtained from the application of the mathematical model, considering the assumptions, the values of the parameters established for the duration of the load, the discharge and the transit time when loaded. The cycle time of the wagon was calculated for the respective month, according to the demand for the period, and these values for the cycles serve as a parameter to perform the sizing of wagons, according to equation 1:

\[
\text{Need of wagons (t)} = \frac{\text{Demand (t) } \times \text{Wagon cycle}}{\text{Useful ton per wagon} \times \text{Days (t)}}
\] (1)

The demand for the period, divided by useful ton per wagon capable of supplying the goods from the origin and destination terminals, results in the amount of cargo needed to accomplish the planned volume. The division by working days allows knowing how many loads per day are needed and, finally, the multiplication by the wagon cycle considers how many times each allocated wagon is loaded in the period. The result after all the operations represents the necessity of allocated wagons to meet the demand of the period for this flow, which is characterized by merchandise, customer, origin, and destination.

Decision Variable:

\[x_{ijk}\] Number of k-type wagons that will be moved from i to j;

Input data definitions precede model assembly:

M: discharge terminal set, \(M = \{1, 2, \ldots, i\}\)

N: charge terminal set, \(N = \{1, 2, \ldots, j\}\)

\(\lambda_{ik}\): offer of wagons k at terminal i

\(\varphi_{jk}\): demand for wagons k at terminal j

\(C_{ij}\): wagon transit time from terminal i to terminal j

D: wagons circulating after unloading, \(D = \{1, 2, \ldots, \lambda\}\)

C: freight wagons arriving at the terminals, \(C = \{1, 2, \ldots, \varphi\}\)

P: routes between terminals i and j, \(P = \{1, 2, \ldots, i \times j\}\)

Objective function:
Equation (2) refers to the minimization of the sum of the empty wagons transit time between the discharge terminals and the cargo terminals:

\[ z^* = \min \sum_{i \in M} \sum_{j \in N} \sum_{k \in V} c_{ij} x_{ijk} \]  

(2)

The restrictions are as it follows:

(a) number of empty wagons which will circulate from each unloading terminal to the loading terminals;

\[ \sum_{i \in M} \sum_{j \in N} \sum_{k \in V} x_{ijk} \leq \lambda_{ik} \quad \forall i \in M, j \in N, k \in V \]  

(3)

(b) number of wagons offered for the load, summing the departures from all origins at the unloading terminals;

\[ \sum_{j \in N} \sum_{i \in M} \sum_{k \in V} x_{ijk} \geq \varphi_{jk} \quad \forall i \in M, j \in N, k \in V \]  

(4)

c) supply of empty wagons for each cargo terminal;

\[ \sum_{i \in M} \sum_{j \in N} \sum_{k \in V} x_{ijk} \leq \Omega_{max} \xi \quad \forall i \in M, j \in N, k \in V \]  

(5)

d) maximum unloading lot per terminal;

\[ \sum_{i \in M} \sum_{j \in N} \sum_{k \in V} x_{ijk} \leq \Omega_{max} \mu \quad \forall \mu \in M, j \in N, k \in V \]  

(6)

e) available wagon allocation to only one cargo terminal at a time;

\[ \sum_{n \in P(i,j)} x_{ijk} n = 1 \quad \forall i \in M, j \in N, k \in V \]  

(7)

f) circulation of all unloaded wagons to any loading terminal;
\[ \sum_{a \in D} s_t = \sum_{d \in C} d_j \quad \forall t \in M, j \in N \]

\(g)\) number of wagons moved from unloading terminals which arrive at loading terminals. 

\[ x_{ij} \geq 0; \quad \forall i \in M, j \in N \]

For solving a minimization problem using the simplex method, we begin by assigning values equal to zero to the variables. Next, the variable that has the greatest interference in the result of the objective function \((z^*)\), called an active variable, is identified. The identification is simple, since the higher the coefficient is, the greater is its interference in \(z^*\). As the value of this active variable increases, the algorithm checks all constraints until one of them is not satisfied, called active constraint. After completing the tests of the first variable, we find the value that optimizes the problem solution, and the procedure is restarted one by one for the other variables until the increment of the variables causes addition of the objective function, and the next value of \(z^*\) increases rather than decreases (TAHA, 2008).

Table 1 presents an example of the parameterization for transit times between the 26 discharge terminals and the 21 steel product loading terminals.

The times between the unloading terminals, listed in the first column and the loading terminals, in the first row, respectively represent the transit time for the carriage of the wagon between them.

| DISCHARGE TERMINALS | LOADING TERMINALS |
|---------------------|-------------------|
| T01                 | T28               |
| T02                 | T29               |
| T03                 | T30               |
| T04                 | T31               |
| T05                 | T32               |
| T06                 | T34               |
| T07                 | T35               |
| T08                 | T36               |

Table 1: Parameterization of transit times between unloading and loading terminals

The model that was developed in the present work was applied in a railway concessionaire in the Southeast region of Brazil. The approved monthly transportation volume was the first input to
determine the average number of wagons each terminal should load and unload per operating day. Thus, applying equation (10) for calculating the number of unloaded wagons per period at the terminals, we obtained the number of empty wagons generated at each unloading terminal according to the demand of each cargo terminal.

\[
Unloaded\ wagons\ (t) = \frac{Demand\ (t)}{\text{Useful ton wagon}} \times \text{working days for unloading}(t)
\]

4 RESULTS

After applying the model to actual data, we obtained the optimized overall empty transit not only for the time of the wagons, but also for the time per flow as well, both based on the wagon distribution identified by the model, and no longer by the return to the previous cargo terminal. Thus, the loading, transit, and unloading times have been defined by the location of the terminals and the circulation among them. Meanwhile, the empty transit time allocates the assets for the next load to minimize the empty wagon time. Figure 3 shows the result of a recalculated cycle, considering the distribution of empty assets by the developed model.

![Fig. 3 Calculation of a flow cycle for minimizing global empty transit time](image)

The overall optimal solution for circulation is shown in Figure 4. Total empty traffic time is the value of the objective function, and the result obtained after 54 iterations were 175.826 days, considering the average demand per day for loading and unloading terminals.

Figure 4 illustrates the property of the proposed model, a Pure Integer Linear Program (PILP). Figure 4 shows that the model has 1,028 variables, which are wagon allocations between discharge and load terminals, and 189 constraints, listed in equations (3) to (10).
Table 2 presents the results: “Value” is the number of wagons that should circulate from one unloading terminal to another loading terminal (“Variable”), that is, there was an allocation of 7 wagons for unloading at terminal “T01”, and then circulating to terminal “T41”, where it should be loaded. It was the only allocation for unloading terminal “T01”. The column “Reduced Cost” shows the cost of inserting a wagon from terminal “T01” to the respective cargo terminals. For all unloading terminals, the model indicates, similar to table 2, how the distribution of the wagons for the unloading operation should be.
5 IMPLICATIONS FOR MANAGERIAL PRACTICE

The sum of the planned empty transit time for all demand wagons considered as a premise before the development of the optimization model was 259.4 days, and applying the model is 175.8 days, that is, a 32.2% reduction in the initial planned time, which represents 7.08% of the initial total planned cycle time. Optimizing empty traffic improves the overall cycle and reduces the allocation of 62 wagons to carry the same volume for the distribution of demand by source and destination, representing an economy of 7.08% of the original allocation of 876 cars. Figure 5 illustrates the comparison of the scenarios before and after applying the optimization model.

Table 2: Results from the origin at terminal 1.

| Variable | Value | Reduced Cost |
|----------|-------|--------------|
| T01LISO_T28LISO | 0.000000 | 2.958.333 |
| T01LISO_T29LISO | 0.000000 | 1.951.389 |
| T01LISO_T30LISO | 0.000000 | 3.020.833 |
| T01LISO_T31LISO | 0.000000 | 1.482.639 |
| T01LISO_T32LISO | 0.000000 | 1.611.111 |
| T01LISO_T34LISO | 0.000000 | 1.527.778 |
| T01LISO_T35LISO | 0.000000 | 1.750.000 |
| T01LISO_T36LISO | 0.000000 | 1.305.556 |
| T01LISO_T38LISO | 0.000000 | 0.3611111 |
| T01LISO_T39LISO | 0.000000 | 0.6458333 |
| T01LISO_T41LISO | 7.000.000 | 0.3611111 |
| T01LISO_T42LISO | 0.000000 | 1.138.889 |
| T01LISO_T43LISO | 0.000000 | 1.097.222 |
| T01LISO_T44LISO | 0.000000 | 1.496.528 |
| T01LISO_T45LISO | 0.000000 | 2.125.000 |
| T01LISO_T46LISO | 0.000000 | 1.097.222 |
| T01LISO_T47LISO | 0.000000 | 0.3611111 |
| T01LISO_T48LISO | 0.000000 | 0.6909722 |
| T01LISO_T49LISO | 0.000000 | 1.750.000 |

Fig. 5: Comparison of original and optimized empty transit time
Figure 6 shows the comparison between the empty transit time of the original planning and the optimized, calculated by the proposed model. There are some shorter times of empty traffic in the initial planning compared to the optimized time, but the sum of empty transit times for the distribution of wagons for the same demand is lower than the original. Another benefit is the reduction in transit time amplitude and variability. Considering the return on rail trains to the previous cargo terminal, while only 63% of the originally planned transit times were less than 37h 8min, after application of the proposed model, 90% of the cargo terminals could be filled with empty wagons less than 37h 4min.

![Comparison of original and optimized empty transit time](image)

Considering $300,000.00 the approximate value of a new platform wagon the potential savings for the scenario is $4,500,000.00 if necessary to purchase the asset to meet the potential volume. The historical volume used in this article shows the growing demand for rail transportation, a fact that increases in the necessity of assets and productivity.

The results contribute to direct the distribution of empty wagons, and to approximate the planned to the actual cycle parameters during the monthly dimensioning of the convoy, the allocation of empty wagons will not necessarily return to the terminal where the wagon had been loaded.

The assumption that the empty wagon always returns to the terminal where it was loaded generates distortions between fleet dimensioning for monthly service and the effective distribution of empty wagons during the monthly service. After the proposed model application, the planned cycle considered the empty traffic according to the best distribution of empty wagons and no more the same terminals for loading and unloading. The cycle and the empty transit are adjusted to the demand between the source and destination terminals during that period and for each volume change.
The initial application of the proposed model has been made in the service of steel products transportation, due to the complexity involved in the distribution of empty wagons, and the quantity of loading and unloading terminals involved in the process. Besides, it contributes for making more assets available for container transportation, as this type of wagon is used for both types of goods. Reducing the need for steel wagons makes available more assets, that can be transferred to container transportation, which increases both steel and container transport volumes.

The proposed model can be adapted to other loads carried through the railway in which the model was applied, besides other railroad networks, with adaptation like predefined lots or prioritization of routes.

The adjustment of the dimensioned cycle enables the execution of a plan that is closer to the operational reality since the empty transit time considers the demand distribution, and the allocation of empty wagons is done by the algorithm optimization, which makes the planning process more assertive, and generates benefits for rail service because allocates the assets needed to transportation their volumes more efficiently and at the same time feasible.

6 CONTRIBUTION TO SCHOLARLY KNOWLEDGE

The present article presents a differential of other allocation models, because it allows the planned wagon cycle adequacy, according to the demand of the respective period, and also has the approach for directing the optimal distribution of the assets using an integer linear programming algorithm.

One of the limitations of the proposed model is that the train grid must be under evaluation and monthly checked by the operational planning area since it provides the parameters of wagon transit times between the terminals represented by the cost \( c_{ij} \) in the objective function of the model. Thus, the grid directly influences the results obtained for the asset distribution orientation for the load terminals.

Next studies can be for using the methodology in short term scheduling, up to two days, to contribute to railway logistics and daily scheduling. Although the present study can be applied for this purpose, it is necessary to integrate real-time location and status information of the entire convoy.

The modernization and application of Operations Research tools on the railroad for increasing productivity of assets also contributes to the increment of the wagons capacity and the reduction of the transportation cost. The optimization model proposed in the present study obtained an empty transit time 32% lower than the original planning, rescued the empty transit time of the wagons, and determined the cycle used for sizing, considering the empty transit time for each load point, according
to the demand distribution by loading and unloading terminals. It was possible to reduce the difference between the planned and the actual cycles, as well as to maximize the productivity of the assets since the model allocates the empty wagons at the cargo terminals where the sum of the empty transit time is the smallest, based on the distribution of demand for the respective period.

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