TRAIN FORMATION PLAN ON HUB–AND–SPOKE NETWORK CONFIGURATION

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The advantages of rail transport over road transport are well recognized from the point of view of the requirements of sustainable development. However, at national as well as European level, the share of freight rail transport is significantly lower than road transport. Subsequently, there are constant concerns for adapting rail freight services to the dynamics of the logistical requirements of the beneficiaries. Outlined in this frame, the purpose of this paper is to identify solutions to increase the efficiency of rail transport.

The paper presents the methodology developed to select an optimal variant of the train formation plan. The indicators defined to compare variants of the train formation plan are analyzed.

Keywords: freight transport, train formation plan, hub-and-spoke network

1. Introduction

Freight transport is an essential component of the economy, ensuring the movement and availability of raw materials and products for manufacture, trade, consumer activities. Therefore, the efficiency of the freight transport system is crucial for well-functioning of the socio-economic environment. But, in the last decades, in land freight transport, the share of road transport has become predominant [1], with significant negative consequences on congestion, pollution, increasing number of accidents [2]. On the other hand, the capacity of the rail system and the advantages of the rail transportation are insufficient utilized [3]. Consequently, research is needed to increase the efficiency of rail transport and to adapt the services to the dynamics of the logistics requirements [4, 5].

In this frame, an important issue consists in applying an appropriate train formation plan (TFP), adjusted to the changing economic and regulatory conditions, which leads to reliable, high quality and low-cost services to the customers [6]. TFP determines routing and frequency of trains and assigns the demands to trains. Proper allocation of railroad car flows based on the systematic improvement of TFP represents an essential condition to ensure a rhythmic and cost-effective activity on railway network.

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The aim of the paper is to develop a TFP based on a hub-and-spoke network configuration. Based on the existing railway network, a hub-and-spoke network structure is designed to concentrate flows in central trans-shipment facilities (technical railway stations and shunting yards). Thus, large numbers of direct connections can be replaced with fewer, indirect connections and allow carriers to take advantage of scale economies through consolidation of flows [7].

TFP based on a hub-and-spoke network aims to fully meet the performance tasks required by customers and increase the profitability of railway transport. It ensures a unitary time and space coordination of the freight train processing as well as of guiding the trains and the groups of freight railroad cars on the whole railway network. It has also the role of ensuring a better correlation of freight and passenger train traffic schedules.

The paper is structured as follows. The next section presents the methodology applied to design a TFP. Then, the indicators defined to compare variants of TFP are discussed. Section 4 presents possible schemes of flow consolidations on a railway route and section 5 outlines the main parameters that influence the results of the TFP.

2. Methodology of TFP

In hub-and-spoke networks, commodities move from the consignor to a home consolidation terminal, then to another destination consolidation terminal and then to the final destination. The modeling of these networks involves the identification of flow consolidation terminals to increase the efficiency, effectiveness and competitiveness of the transport services provided [2, 4]. The processes of flow consolidation in the initial consolidation terminals, respectively decomposition in the initial consolidation terminals lead to disadvantages: increased transport duration, increased vulnerability of services due to delays and congestion that may occur in hub terminals. Therefore, the configuration of a hub-and-spoke network must ensure the organization of services with the benefit of compensating for the disadvantages introduced in relation to the direct connections between the point of origin and the point of destination.

For the configuration of the hub-and-spoke railway network, the following categories of stations are considered as potential terminals for consolidating traffic flows (Fig. 1):

- - *Shunting yards* - are intended for consolidation by decomposing the wagon flows, their accumulation and grouping in the composition of the train according to their final destination and then shipping on the arches of the network. In this way, each possible origin-destination combination can be served without providing a large number of connections between network nodes [8].

- *Technical stations* - have several groups of specialized lines and facilities specific to local traffic with large volumes of activities (traffic, shunting, commercial). Trains with isolated wagons or groups of wagons from their own area of influence (or from other sorting, technical or intermediate processing stations destined for their own area of influence) arrive at these stations. Technical stations may form direct freight trains or wagon groups which are attached to multi-group trains for any sorting, technical or intermediate processing station.
- - *Intermediate processing stations* - have much smaller activities and areas of influence compared to those of technical or sorting stations. They enter the area of influence of the technical or triage stations, can receive trains with isolated wagons both from the stations in their own area of influence and from the network triage / technical stations and have as destinations only stations in their area of influence.

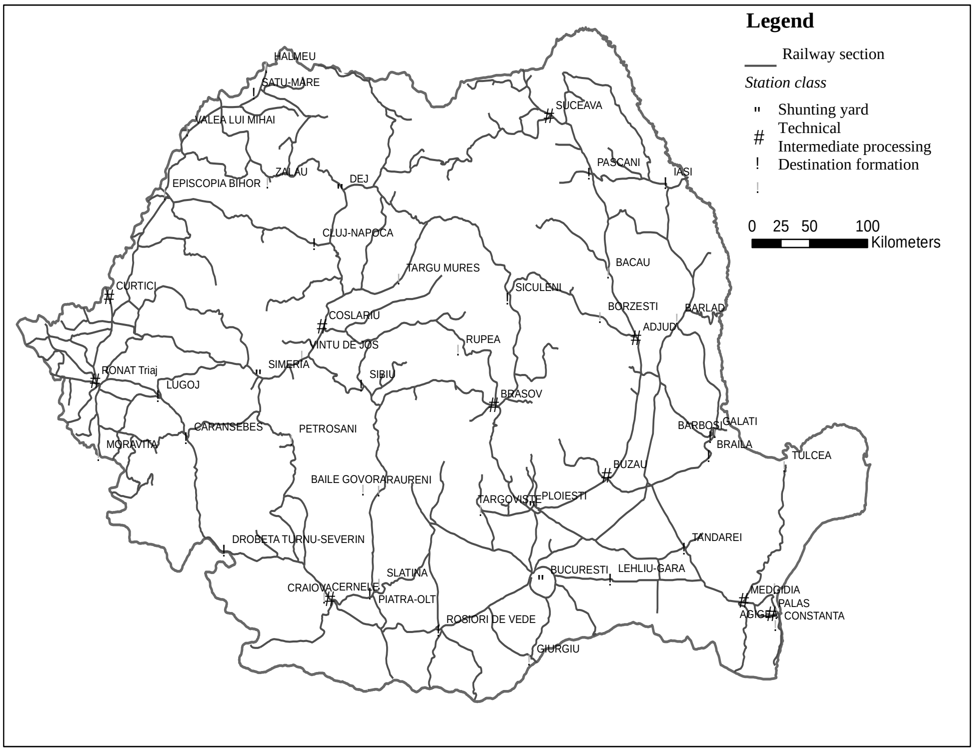

Fig. 1. The Romanian railway network with the stations included in the initial set of potential consolidation terminals

The TFP aims to cost-effectively allocate the shunting and sorting operations on the hub-and-spoke railway network [9]. Starting from the set of the presented station classes, variants of the TFP are analyzed. The optimal variant is selected by a set of defined criteria.

The TFP can be considered a unique technological process at the level of the entire railway network, for all stations, for assigning the processes for shunting freight railroad cars between stations [9, 10]. It shall include both freight trains in which freight flows are high and other freight trains (direct, section and local trains). During designing the TFP, it is necessary to analyze the technical endowments of the railway stations, the maneuvering and sorting capacity, as well as the endowment of the goods handling fronts (loading - unloading) and their degree of mechanization an automatization.

The following steps are followed to identify the optimal variant the TFP:

- Collecting the data regarding the technical equipment of the rail stations (number of maneuvering and sorting lines, processing capacity of the sorting hump and pulling lines as well as the capacity to handle goods at the loading and unloading fronts of the station, etc.).
- Selection of the stations where freight trains can be formed and from which railroad car flows from their area of influence are processed and shipped.
- Establishing the railroad car flows scheduled for the entire validity period of the TFP.
- Choosing of the train types running on the railway network with special codes appointed to the new formed freight trains.
- Assigning the shunting activity among railway yards according to their processing capacity and the technical equipment necessary to perform these operations.

3. Variants of TFP

The main procedure of the train formation plan is to identify the difficulties of the technical stations and shunting yards of the hub-and-spoke network in fulfilling the tasks of the current formation plan and the possibilities to eliminate these problems. To define and compare the indicators for different TFP variants, the following notations are used:

N_{pr} - the number of wagons being processed ;
k - number of destinations corresponding to freight trains ;
c - the accumulation parameter ;
m - the number of (conventional) wagons in the train structure ;
t_{tranz} - the average standstill time of a wagon running with the trains in transit;
t_{pr} - the average standstill time of a wagon for processing ;
t_{ec} - time savings for the case when the wagon would transit the technical station (or shunting yard) without processing ;
c_{pr} - the costs (in monetary units) for the processing of a railroad car

c_{tranz} - the costs for the railroad car that is in transit

c_{vgh} - the costs of a railroad car - hour standstill time for the entire railway analysis network

Mainly, the analysis of the variants of TFP aims to compare the following indicators [11]:

- *the railroad car-hours consumption for accumulation ($\sum k \cdot c \cdot m$)* - represents the sum of the product between the value of the parameter of accumulation of freight trains, the number of conventional railroad cars in the composition of the train set and the number of destinations for which the accumulation is performed.
- *the railroad cars – hours consumption for processing ($\sum N_{pr} \cdot t_{ec}$)* - represents the sum of the product of the number of railroad cars processed and the time savings resulting from the transit of railroad cars without processing or the time savings calculated based on the cost of processing a single railroad car.
- *the level of utilization of the processing capacity of the stations*.
- *number of destinations* corresponding to freight trains.
- *the number of railroad cars dispatched* by run-through trains.
- *daily average distance of railroad cars* expressed in the number of kilometres travelled daily by each railroad car within the active fleet.
- *average journey covered by the railroad car between two successive processes.*

The identification of the optimal variant of the freight train formation plan must be made starting from the comparison of the established indicators of each possible variant of it. Due to the multitude of these indicators (which lead to laborious calculations), a way to reduce the criteria for establishing the optimal variants of the training plan must be identified.

A first criterion of comparison is the economic one. This leads to the determination of the monetary expenses corresponding to each variant. It should be noted that the existing technical equipment (processing capacity of stations, number of lines in sorting stations, etc.) is also considered. These expenses are computed as [11]:

$$C = \sum N \cdot t_{tranz} \cdot c_{vgh} + \sum kcm \cdot c_{vgh} + \sum N_{pr} \cdot t_{ec} \cdot c_{vgh} + \sum N_{pr} \cdot \left(c_{pr} - c_{tranz}\right) \qquad (1)$$

The first term in eq. (1) is constant whatever the allocation of the railroad car flow is considered. Therefore, for further analysis of the costs of the different variants, this term can be excluded. Let denote $\Delta C = C - \sum N \cdot t_{tranz}$. Dividing by c_{vgh} both terms of eq. (1), we obtain:

$$\frac{\Delta C}{c_{vgh}} = \sum kcm + \sum N_{pr} \cdot t_{ec} + \sum N_{pr} \cdot \frac{c_{pr} - c_{tranz}}{c_{vgh}} \qquad (2)$$

Based on the relation (2), it can be observed that, to assess the effectiveness of the different variants of the train formation plan, it is necessary to determine the consumption of railroad cars-hours of each variant.

Moreover, it can be stated that this indicator is the most complete, being able to establish the variants of the TFP involving the lowest operating costs. To the multitude of indicators of each variant the number of flow combinations is added and is calculated as $2^{(n-1)(n-2)/2}$ [11, 12]. E.g., the case of a railway line with seven technical stations, we obtain $2^{(n-1)(n-2)/2} = 32768$ practically possible variants of TFP. Consequently, the calculation volume for identifying the optimal variant is high, although it involves the analysis of a single indicator.

If we consider the combinations of all flows (neighbouring and non-neighbouring), the number of these variants increases rapidly. In addition to the analysis of the variants of the train formation plan, a series of parameters - railroad car flows, accumulation parameter, railroad car idle time in technical stations, processing equivalent - significantly influence the choice of the optimal variant. These specific aspects are discussed in the next sections.

4. Flows consolidation schemes and idle time

The railroad car flows necessary for the freight train formation plan are obtained starting from the values of the freight flows. The number of railroad cars is a size depending on the type of goods transported, the nominal load capacity of the railroad cars used and their degree of use. The daily railroad car flow is:

$$N_{vg} = \frac{Q_{anual} \cdot k_n}{365\left(\alpha_2 \cdot k_2 \cdot q_{n2} + \alpha_4 \cdot k_4 \cdot q_{n4} + \alpha_6 \cdot k_6 \cdot q_{n6}\right)} \text{ [railroad cars]} \qquad (3)$$

where

Q_{anual}	is	annual transport volume expressed in net tonnes;
q_{n2}, q_{n4}, q_{n6}	-	loading capacity of railroad cars on two, four and six axles;
$\alpha_2, \alpha_4, \alpha_6$	-	the percentage of two, four and six-axle railroad cars in the fleet;
k_2, k_4, k_6	-	the loading capacity usage coefficients of the railroad cars on two, four and six axles;
k_n	-	irregularity traffic coefficient.

For the precise determination of the railroad car flows it is necessary to identify the directions of travel for which the formation plan of the freight trains is elaborated and subsequently the basic technical stations are chosen. Another element to be considered is the fact that these railroad car flows appear and go out in several basic technical stations in the entire railway network of the respective regions. Figure 2 exemplifies the schemes of railroad car flows resulted after calculation for the case of a railway line with seven basic technical stations.

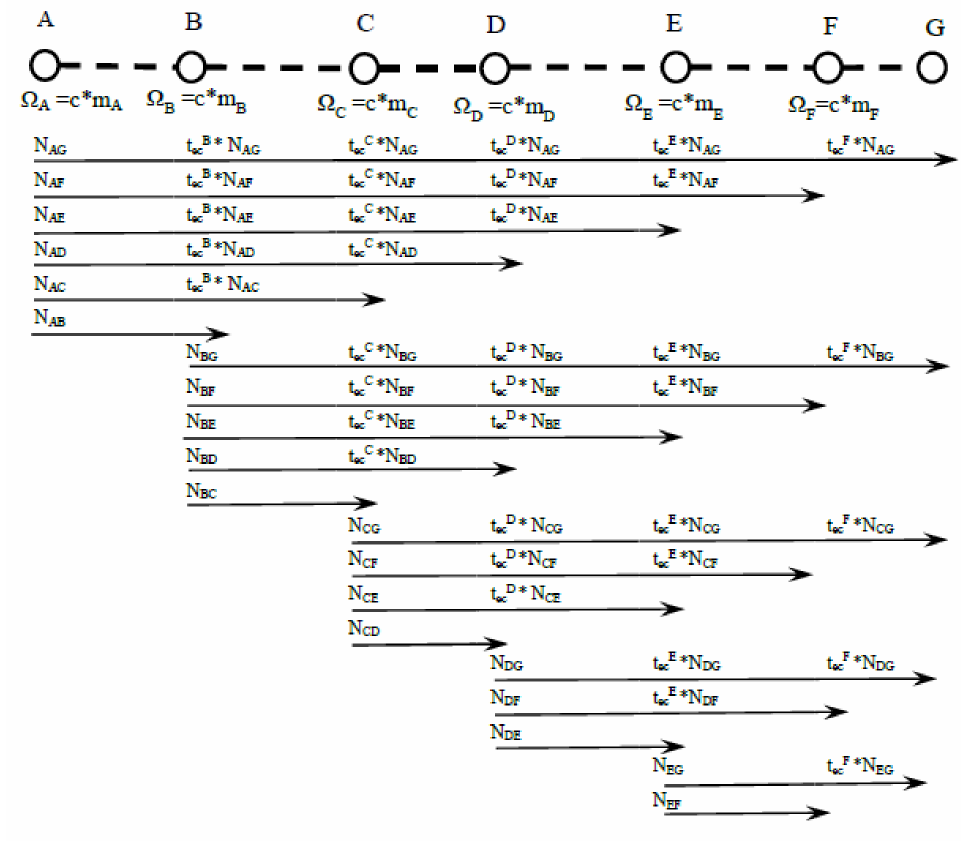

Fig. 2. Schemes of railroad car flows for a railway line with seven main technical stations

The destination chart of railroad car flows is the starting point in identifying the optimal variant of the freight train formation plan. As it can be seen, the freight railroad cars movement through the technical stations of the railway network generates time savings for each railroad car. This value shall be determined for each individual technical station and shall be considered both the time rules laid down for carrying out technological operations on the railroad cars and the train traffic schedule. To calculate this time saving, it is not necessary to consider the accumulation time. This is explained by the fact that, when the railroad car flows transit through the shunting yard, its size is reduced. The effect of this reduction is reflected in the increase in storage time for the rest of the processed railroad cars. Despite this, the total railroad cars-hours consumption for accumulation for all railroad cars does not change.

Assuming the case of the specialization of a beam N_1 transiting from the size of the current N of railroad cars passing through a shunting yard, the time savings obtained because of avoiding processing will be $N_1(t_{prel} - t_{ac})$ (in this expression, t_{prel} refers to the railroad cars average idle time during processing and t_{ac} at the average standstill time of a railroad car for accumulation).

Therefore, the accumulation time of a single railroad car will increase from the value $c \cdot m/N$ to $c \cdot m/(N - N_1)$. Assuming that the accumulation parameter c remains constant, then [11]:

$$\left(N - N_1\right) \cdot \left(\frac{cm}{N - N_1} - \frac{cm}{N}\right) = N_1 \cdot \frac{cm}{N} = N_1 \cdot t_{ac} \tag{4}$$

The time saving results:

$$N_1 \cdot \left(t_{prel} - t_{tranz}\right) - N_1 \cdot t_{ac} = N_1 \cdot \left(t_{prel} - t_{tranz} - t_{ac}\right) \tag{5}$$

where t_{tranz} represents the average idle time of a railroad car that travels with trains in transit. If we relate this saving to a single railroad car in the composition of the freight train, we will obtain:

$$t_{ec} = t_{prel} - t_{tranz} - t_{ac} \tag{6}$$

Thus, the railroad cars standstill time in a technical station can be calculated with a relationship that considers the size of the current of railroad cars that are processed and consumed by railroad cars - accumulated hours. Let denote N_{tranz} the transit flow and N_{prel} the size of the railroad car flow being processed. Then the railroad cars idle time in a technical station of the hub-and-spoke railway network is:

$$t_{teh} = N_{prel} \cdot t_{prel} + N_{tranz} \cdot t_{tranz} \tag{7}$$

By substituting eq. (6) in eq. (7), we obtain:

$$t_{teh} = N_{prel} \cdot t_{ec} + \left(N_{tranz} + N_{prel}\right) \cdot t_{tranz} + kcm \tag{8}$$

where k considers the number of destinations of the formed trains and cm is the railroad cars-hours consumption for the accumulation. Eq. (8) shows that the term $(N_{tranz} + N_{prel}) \cdot t_{tranz}$ has a constant value. For the optimal variant of TFP we are interested only in the variable term of eq. (8). Therefore, the next expression represents that part of idle time that is influenced by the way of organizing the railroad car flows (more precisely, by the TFP design). This can be expressed as:

$$\sum t_{teh} = \sum N_{pr} \cdot t_{ec} + \sum k \cdot c \cdot m \tag{9}$$

where $\sum t_{teh}$ represents the component of the idle time in the technical stations which is dependent on the TFP design. If in eq. (9) the size of the processing equivalent, r, is also considered, we obtain the expression of the consumption of railroad cars-equivalent hours for idle time in the technical stations:

$$\sum t'_{teh} = \sum N_{pr} \cdot \left(t_{ec} + r\right) + \sum k \cdot c \cdot m \tag{10}$$

Figure 3 shows the variations of the idle time for different ways of organizing railroad car flows due to variations of terms $\sum N_{pr} \cdot t_{ec}$ and

$\sum N_{pr} \cdot (t_{ec} + r)$ respectively. It resulted the value of the number of processed railroad cars which corresponds to a minimum value of the two functions. In this case, it can be stated that there is a TFP variant that leads to a minimum idle time of railroad cars in the technical stations on a certain railway line. Therefore, by a judicious organization of the railroad car flows, an acceleration of the railroad car turnover can be obtained.

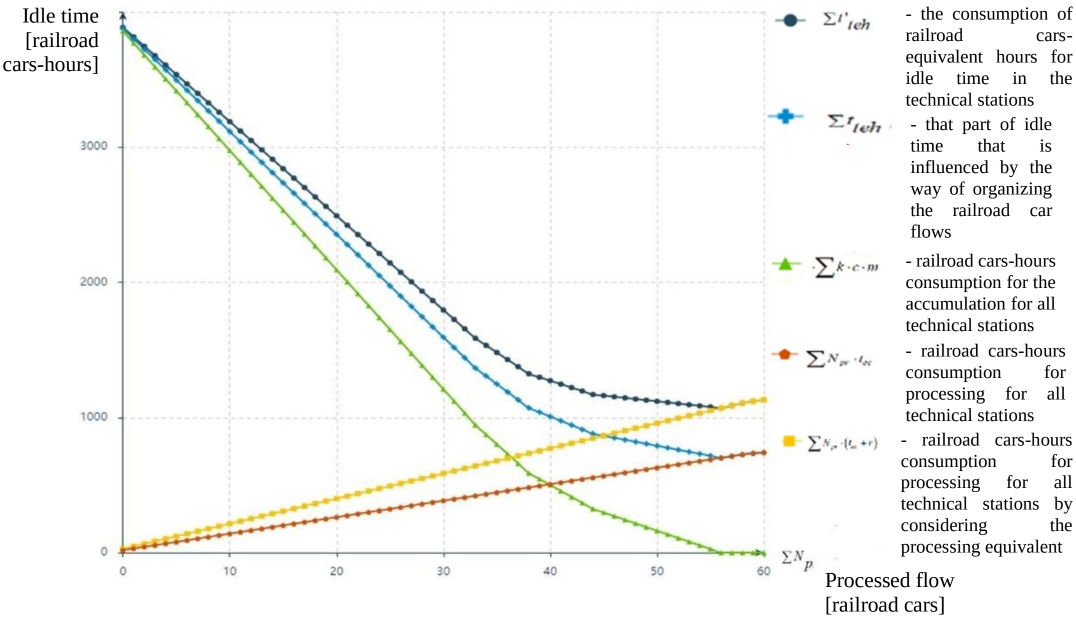

Fig. 3. Variations of the idle time

5. Accumulation parameter and processing equivalent

Another measure that influences the process of accumulation of railroad cars in the shunting yards (and, implicitly, on the choice of the optimal TFP variant) is the accumulation parameter. Through the values it can take, the accumulation parameter highlights the influence on:

- time intended for the accumulation in the station of the railroad cars for an established destination (which can be of maximum 24 hours)
- the frequency of the accumulation process of freight railroad cars (parameter γ)
- parameter g_{vg} indicating the size of the group of railroad cars from which the respective set accumulate.

Parameter g_{vg} shall be calculated as the ratio between the number of trains arriving at the station containing railroad cars for a given destination and the number of trains which have been dispatched from the station for that destination. The equation can be written as follows:

$$g_{vg} = \frac{n_{tr,sos}}{n_{tr,exped}} \tag{11}$$

By introducing the eq. (11) in the expression of the accumulation parameter, we obtain that:

$$c = 0,5 \cdot T_{ac} \cdot \left(1 - \frac{n_{tr,exped}}{n_{tr,sos} \cdot \gamma}\right) = 12 \cdot \left(1 - \frac{n_{tr,exped}}{n_{tr,sos} \cdot \gamma}\right) \tag{12}$$

Based on eq. (12), the variation of the accumulation parameter will be analysed for a number of trains that were dispatched between 1 and 15 and for values of the parameter γ corresponding to the frequency of interruptions occurred during the accumulation process equal to 1 and 2. The variations of the accumulation parameter are illustrated in Figure 4.

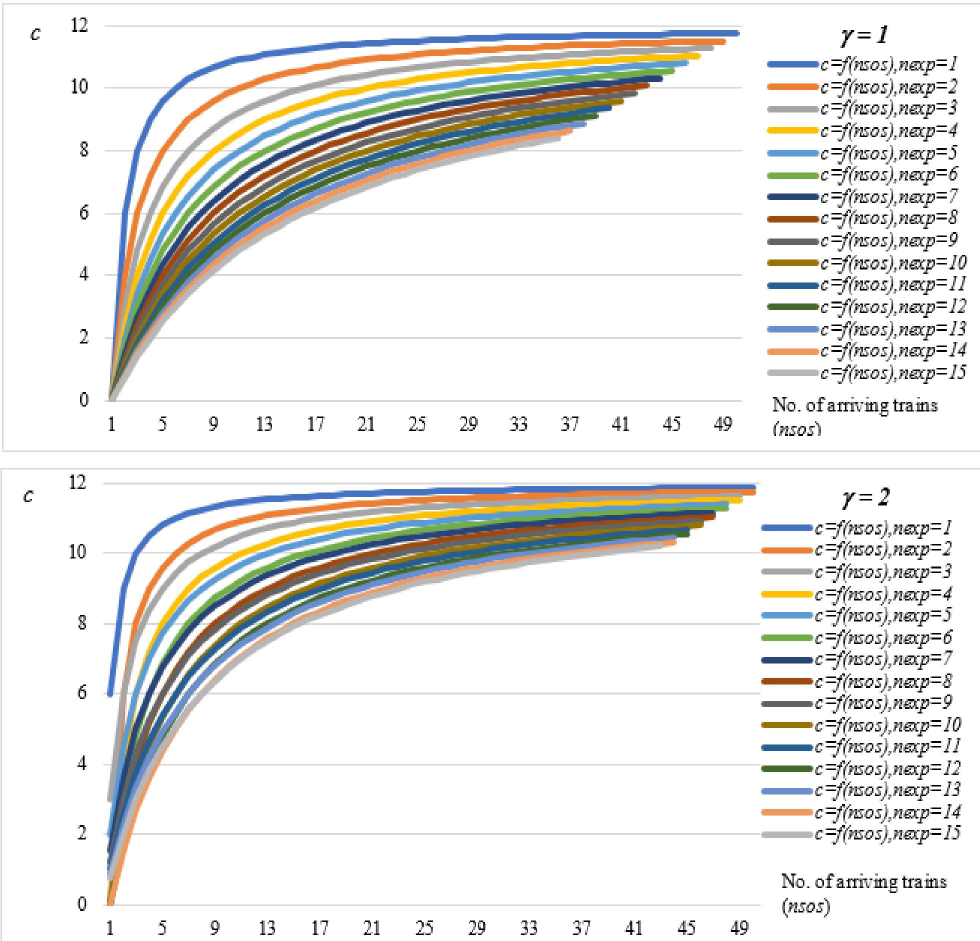

Fig. 4. Variation of the accumulation parameter for frequency of interruptions $\gamma = 1$ *and* $\gamma = 2$

It can be observed that this indicator decreases simultaneously with the increase of the current of railroad cars to be shipped for the same values of $n_{tr,exped}$. Also, the accumulation parameter tends to decrease with the reduction of the number of trains arriving at the station containing railroad cars for a certain destination $n_{tr,sos}$ as well as an increase due to the increase of the value of the parameter γ. From the eq. of the accumulation parameter, it results that it is directly proportional to the half of the period destined for the accumulation of the freight railroad cars in the station for a certain destination from which all the times of interruption of the accumulation process have been deducted.

If the number of trains arriving at the station containing railroad cars for a given destination is replaced by the ratio between the duration for the station to accumulate railroad cars for that indicated destination and the time interval between the arrival of two trains, I_{sos}, the eq. (12) can be written as:

$$c = 0.5 \cdot T_{ac}\left(1 - \frac{n_{tr,\exp ed} \cdot I_{sos}}{T_{ac} \cdot \gamma}\right) \tag{13}$$

The eq. (13) of the accumulation parameter emphasizes that it is directly proportional to the half of the period intended for the accumulation of freight railroad cars in the station for a certain destination from which all interruption times in the accumulation process have been deducted. The relation can be used only in the conditions of a uniformity in time and in size of the group of railroad cars, fact that leads to the idea of modifying this equation by introducing the following coefficients [13]:

- α_t, the coefficient that quantifies the conditions of arrival of railroad car groups on time, computed as a ratio between the duration of station railroad cars for accumulation and the duration of stationing in the event of a uniform arrival of railroad car groups:

$$\alpha_t = \frac{\sum_{i=1}^{n} t_{ac,i}}{0,5 \cdot t_{acum} \cdot (g-1)} \tag{14}$$

- α_n, the coefficient which tracks the arrival of groups as number of railroad cars, calculated as the ratio between railroad cars-actual accumulation hours (T) and railroad cars-accumulation hours which may occur in the case of groups equal to $(m\text{-}m_0)/(g\text{-}1)$ railroad cars during $\sum_{i=1}^{n} t_{ac,i}$ period (where m is the size of the gasket that is formed and with m_0 the size of the final group):

$$\alpha_n = \frac{n \cdot t_a \cdot (g-1)}{\sum_{i=1}^{n} t_{ac,i} \cdot (m - m_o)} \tag{15}$$

- α_m, the coefficient that allows to take into account how the final group of railroad cars influences the accumulation process, and which is determined as a ratio between the average size of the group of railroad cars - with the exception of the final group (m-m_0)/(g-1), and the average size of the group in the composition of a gasket (including here the final group m/g):

$$\alpha_m = \frac{g \cdot (m - m_o)}{m \cdot (g - 1)} \tag{16}$$

Considering these parameters and adding them in the calculation expression of the accumulation parameter, we obtain [13]:

$$c = 0,5 \cdot \left(T_{ac} - \frac{n_{tr,\exp ed} \cdot I_{sos}}{\gamma} \right) \cdot \alpha_t \cdot \alpha_n \cdot \alpha_m \tag{17}$$

Another factor with a direct influence on the process of railroad car accumulation is the number of destinations for which the specialization of trains is made. Thus, the expressions of the accumulation parameter show that the number of trains dispatched for a specific destination influences the size of the accumulation time of a freight railroad car, which leads to the idea of an interdependence between the accumulation parameter and the number of destinations for which is achieved accumulation. Thus, we can deduce the following calculation relation of the accumulation parameter [7]:

$$c_k = 0,5 \cdot T_{ac} \cdot \left(1 - \frac{\sum_{i=1}^{k} n_{\text{int}\, r,i}}{k \cdot \sum_{i=1}^{n} n_{sos,i}} \right) \tag{18}$$

In addition to the accumulation parameter, another element with a direct influence on the comparison of the variants of the freight train formation plan is the *processing equivalent*. It allows the equivalence of railroad cars-processing hours in railroad cars-stationary hours, being a quantity that characterizes the efficiency of the processing activity in a certain station. The processing equivalent is [11]:

$$r = \frac{c_{pr} - c_{tranz}}{c_{vgh}} \tag{19}$$

The determination of the railroad car processing expenses is based on the expense of manoeuvring activity, which has a significant share of the total expenses of processing a railroad car and all other expenses of the station related to railroad car processing [11].

This category of expenses is influenced by the technical equipment of the station (whether the shunting yard is equipped or not with a sorting hump). The expenses related to the transit of railroad cars without processing are specific to each technical station. These include the expenses with the salary of the workers and civil servants, the maintenance and amortization of the receiving - shipping lines, etc.

The costs for transit without processing are also specific to each station of the hub-and-spoke railway network. This category includes the expenses with the salary of workers and civil servants (their activity is related to the transit of trains, the technical and commercial overhaul of trains), the expenses regarding the maintenance and depreciation of the receiving-shipping lines, etc.

Therefore, to determine the processing equivalent, the values of the parameters c_{pr} and c_{tranz} for each technical station in the railway hub - and - spoke network must be known, as well as the cost of a stationary railroad car - hour for the entire network. Thus, it is necessary to know the size of the processing equivalent for each technical station of the bus to be considered when developing the train formation plan. This is justified by the fact that, when comparing the different variants of the training plan, the railroad car-equivalent hours indicator given by this parameter can be considered.

6. Conclusions

One of the methods used to streamline the processes of consolidating freight flows throughout the hub-and-spoke railway network is to identify the optimal variant of the freight train formation plan. he main advantage of developing the freight train formation plan is the achievement of significant savings by reducing the railroad cars standstill and the time required to carry out consolidation operations (accumulation and processing) of railroad cars. Furthermore, it allows a uniform distribution of shunting activity between stations in accordance with the processing capacity and operating characteristics of each technical station.

Each of the parameters mentioned in the paper (railroad car flow size, standstill time in the technical stations of the rail hub – and – spoke network, the accumulation parameter, and the processing equivalent) have a significant influence on identifying the optimal variant of the train formation plan. For instance, the organization of railroad car flows is highly influenced by railroad cars standstill time for accumulation in technical stations or shunting yards of railway hub-and-spoke network.

The accumulation parameter is directly proportional to the irregularity coefficient of railroad cars arrival and its size reduces as the arrival interval of railroad car groups for a direction increases. In the process of identifying the optimal variant, it is of great importance to know the value of the accumulation parameter for all technical stations and shunting yards of the rail hub – and – spoke network. The size of all these parameters mentioned has a great influence the optimal variant, no matter which mathematical models or algorithms are used for the train formation plan.

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