University POLITEHNICA of Bucharest

Transport Doctoral School

Decision nr :

DOCTORAL THESIS

Transport networks with flow consolidation

Author : As. drd. eng. Armand – Șerban STERE

Scientific coordinator: Prof. dr. ing. Șerban RAICU

DOCTORAL COMMITEE

President		from	
Scientific coordinator	Prof.emerit.dr.ing. Șerban RAICU	from	UPB
Referent		from	
Referent		from	
Referent		from	

Bucharest, 2022

TABLE OF CONTENTS

1. INTRODUCTION

1.1. Necesity and opportunity of research topic

The effectiveness and efficiency of the freight transport sector are fundamental to ensuring the sustainable development of any region (Raicu, 2007; Ogryzek, 2020). The continuous evolution of the interdependencies between the freight transport sector and the socio-economic environment requires multi- and interdisciplinary research on territorial structures and their dynamics (Raicu and Costescu, 2016; Gattuso and Malara, 2020).

The delicate issues in these transport networks relate to delays in the distribution process and the decrease in service reliability as a result of additional processes regarding the consolidation and handling of goods at terminals. It is necessary to study all the stages of consolidation starting from the transport demand consolidation, a process influenced by the non-uniform characteristics of demand (fluctuations over a period of time in terms of volumes to be transported, the role of deposits in consolidating demand. and their proper sizing, the different degree of load of the machines, the number of machines that generate minimum operating costs, etc.).

Another issue that needs to be carefully considered is the establishment of traffic entities. Satisfying the main objective of European policies in the field of increasing the profitability of rail transport involves resorting to mathematical models and algorithms that streamline rail traffic flows. The way in which rail transport is organized must be monitored, ie whether traffic entities will be set up for a single destination or for multiple destinations. At the same time, these models must ensure the widest possible distribution of the transport volumes needed to be consolidated in the technical and triage stations of the railway network.

Thus, it is observed that problems that occur in flow consolidation networks are represented by their configuration, streamlining the processes of consolidation of transport flows and traffic flows. The increasingly stringent requirements for the consumption of material and energy resources, imposed by the objectives of sustainable development, added to the increasingly difficult demands of the beneficiaries, in the conditions of globalization and specialization of production require further research to plan the transport of goods.

1.2. Literature review

In carrying out this thesis, solutions were considered for problems on the accumulation of transport requests in order to establish transport flows, the configuration of networks to consolidate transport flows, the formation of traffic entities. The analyzes presented are based on numerous specialized papers, which can be divided into four thematic groups, presented in Table 1.1.

Tabel 1.1. Bibliographic references used in the elaboration of the doctoral thesis

Main thematic group	Main bibliographic referneces
1. Mathematical models of queuing systems for consolidating transport demand	Ackoff et al. 1975; Boldur – Lățescu et al. 1979; Raicu și Mașală 1981; Hall 1990; Pepe de Gove 1995; Raicu și Costescu 2006; Raicu, 2007, Raicu et al. 2008, Raicu et al. 2011, Adan et al. 2015; Notteboom et.al. 2020.
2. Mathematical models of organization and formation of traffic entities	Frîncu et al. 1965, Săndulescu 1965; Kocinev și Maksimovici 1969; Raicu și Mașală 1981; Cordeau et. al. 1998; Raicu et al. 2010; Shafia 2010; Yaghini et al. 2011; Yaghini et al. 2014; Bohlin și Gestrelius 2015; Xiao et al. 2016; Butko et al. 2017; Lin 2017; Raicu et al. 2018; Xiao et al. 2018; Raicu et al. 2020.
3. Configuration of transport networks with flow consolidations	O'Kellly et al. 1994; Pepe de Gove 1995; O'Kelly 1998; Bontekoning, 2006, Raicu 2007, Bowersox 2007, Costescu 2010, Raicu et al. 2012, Raicu și Costescu, 2012, Crainic et al. 2013, Schönemann 2016, Rodrigue et al. 2020; Raicu și Costescu 2020.

Main thematic group	Main bibliographic referneces
4. Mathematical models for locating transport flow consolidation terminals	O'Kelly 1986; Campbell 1994; O'Kelly şi Bryan 1998; Campbell şi Ernst 2005; Limbourg 2007; Alumur şi Kara 2008; Alumur 2009; Costescu 2010, Raicu et al. 2011; Alumur şi Kara 2012; Farahani et al. 2013; Zabihi şi Gharakhani 2018; Azizi 2019; Fernandez şi Sgalambor 2020.

The first research on identifying the optimal option for setting up railway traffic entities involved the use of a method that successively developed variants closer to the one considered optimal using conditions of "necessity" and "sufficiency". Such methods have required the use of simplifying assumptions that remove the certainty that the identified variant ensures the optimum. These methods were later improved by Soviet specialists, but involved a large volume of intuitive calculations (Tomescu et al., 1961). Other methods for determining the optimal option for setting up railway traffic entities are those of analytical comparisons, conjugate analytical comparisons, but also the heuristic method. Subsequently, models were introduced that allow the establishment of traffic entities for a single destination or for multiple destinations (such as the cases of grouped trains, monogroups, trains composed of empty wagons, etc.).

The formation of multi-destination railway traffic entities has been an issue that has often been addressed separately. The first such mathematical modeling was proposed by Bodin (Bodin et al. 1980) as an integer nonlinear programming problem. Newton et al. (1998) and Barnhart et al. (2000) describe this problem as a network design, with nodes and arches representing technical or triage stations (Zhu and Crainic, 2014).

In 1998, Cordeau et al presented a synthesis of the optimization models for the rail transport problems studied so far. For each category of problems, model classifications are proposed and describe their important characteristics, the emphasis being on the structure of the model, on its algorithmic aspects as well as on routing and programming problems (Cordeau et. Al, 1998). They considered these to be the most important components of rail transport planning activities. Ahuja et al. (2007) propose an algorithm based on a metaheuristic search method for solving the problem of integer formation of grouped trains. This method was intended to address large issues. Shafia and co-workers propose an integer programming model for freight train formation plan issues if input data is subject to uncertainty (Shafia et al., 2010).

As the optimal solution of the proposed model is considered difficult to identify, a eurisistic approach is presented to find a solution close to the optimal one.

Zhu and Crainic (2014) include the formation of railway traffic entities in a framework for modeling tactical planning decisions for rail freight services. The proposed model integrates the selection and scheduling of transport services, train classification, train training and dispatch. The model is based on a spatio-temporal representation structured on three levels of the associated operations and decisions, of the relations between them, as well as of their temporal dimension.

2. TRANSPORT DEMAND CONSOLIDATION

2.1. Transport demand characterization

It is necessary to understand the consolidation process in order to establish more easily the objectives and restrictions that could be formulated in the configuration of a transport network with flow consolidations. First of all, a conceptual delimitation must be made between the notions of transport demand, freight flow, transport and traffic (Figure 2.1).

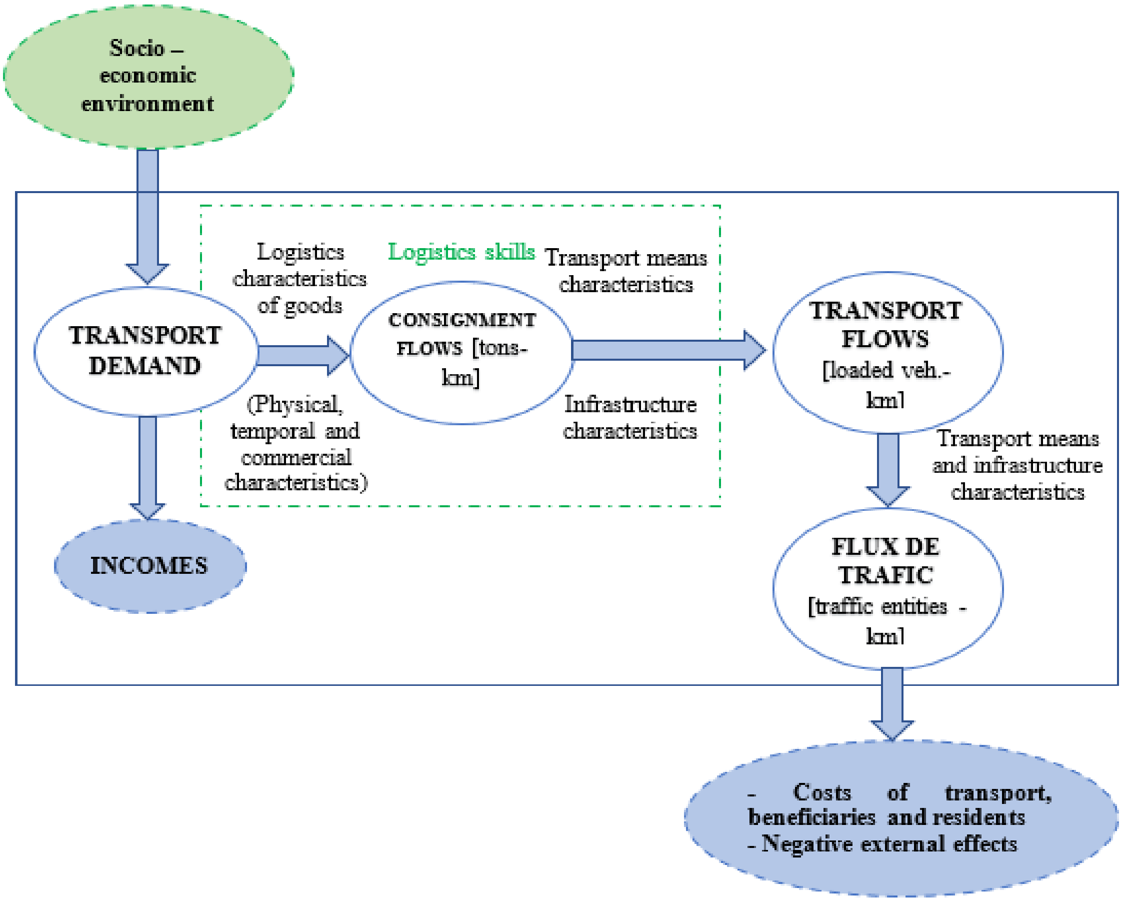


Figure 2.1. Transport demand transformation in consingment flows, transport and traffic flows (Source : adapted after (Raicu, 2007))

With regard to transport demand, the way in which economic activities are distributed in space, both locally and regionally, must be taken into account. In the case of transport of goods, transport demand refers to the need to move goods and is characterized by the pairs of origin - destination, size and structure that are correlated with land use decisions. It is observed that transport demands, which result from the needs of all socio-economic activities, gradually lead to the emergence of flows of goods, transport and traffic (Raicu, 2007). The transport demand is characterized in terms of the quantity that is the subject of the transport service, the existence of deadlines that are decisive for the organization of the activity as well as the commercial characteristics.

The next step in the technology of flow consolidation networks is the merging of transport requests into freight flows taking into account the logistical characteristics of the goods. Freight flows are those groups of goods that are collected / delivered by the same carrier (who always uses the same route and the same means of transport) to the same consignee.

Commodity flows are characterized by the total volume and destination that are established in relation to the market channel. The size of the shipment depends on the volume and frequency of the service as well as the structure of the flow (Raicu and Costescu, 2012). Consolidation of comodity flows involves the unification of small flows of goods from one or more suppliers and intended for one or more customers.

Commodity flows, depending on the characteristics of the means of transport and the infrastructure, are transformed into transport flows and subsequently into traffic flows. The transport flow is measured by the number of loaded transport units (vehicles, trains, ships, aircraft, etc.) multiplied by the distance traveled (thus resulting in train unit km, vehicles km, etc.). Transport flows can be related to transport units (tonne km, passenger km, etc.) or to the unit of time (calendar or operational). The main advantages of such units are that they are additive and partly directly related to the transport demand and that the disadvantage is that they do not fully characterize the transport flow (Raicu, 2007).

The traffic flow is the combined and varied overlap of transport flows but also of other flows of means of transport or unloaded entities, respectively of technological flows (intended for the operation of the system) on the elements of infrastructure (Raicu, 2007). For a detailed characterization of traffic flows, their physical characteristics (size, heterogeneous structure and synthetic parameters of traffic organization) as well as the effects felt by the participants (exogenous or environmental, respectively endogenous) must be taken into account.

Therefore, in order to streamline the transport service provided, one solution is to strengthen transport demand. Such an approach aims at coordinating several suppliers to ship their goods to a consolidation terminal and to collect all requests so that they can be delivered in a single transport unit to a single destination.

2.2. Demand accumulation for transport flows formation

2.2.1. Warehouses

2.2.1.1. Warehouses role in transport flow formation

In the process of consolidating transport demand, one of the important roles in ensuring the continuity and connection between long-distance and accumulation transport, respectively distribution over medium and short distances, is played by the warehouse. Warehouses are an essential component of supply and distribution chains, their roles being to provide a buffer zone for material flows, to adapt to the variation caused by factors such as uneven demand for goods, strengthening demand from various suppliers for combined delivery to customers, but also for the realization of value-added processes that lead to the satisfaction of specific requirements of the final beneficiaries (eg packaging, labeling, product customization, etc.) (Gu et al., 2007). In order to streamline the process of consolidating transport demand, one of the main issues to consider is the proper sizing of the warehouse where the goods will be stored.

2.2.1.2. Probabilistic model for warehouse sizing

One of the main operating conditions of a warehouse is the existence of a free storage area. Goods arriving at the warehouse may be rejected if the storage area is fully utilized. The modeling of these systems is based on the relationships and conditions defined between the waiting points and the serving stations, which aim to transform the input flow into the output stream as a result of the serving activities. The arrangement of the service stations (in series and / or in parallel), as well as the conditioning between them define the typology of the system.

Warehouses can be assimilated with queuing systems for sizing problems that involve determining the optimal number of compartments (so as to ensure the lowest possible probability of rejection for the storage of incoming goods), the size and capacity of warehouses, the type of handling equipment (Masek et al., 2015). The representation of the warehouse as a queuing system is illustrated in Figure 2.2, where we can see that to determine the storage capacity it is necessary to know the probability of refusal of stored applications.

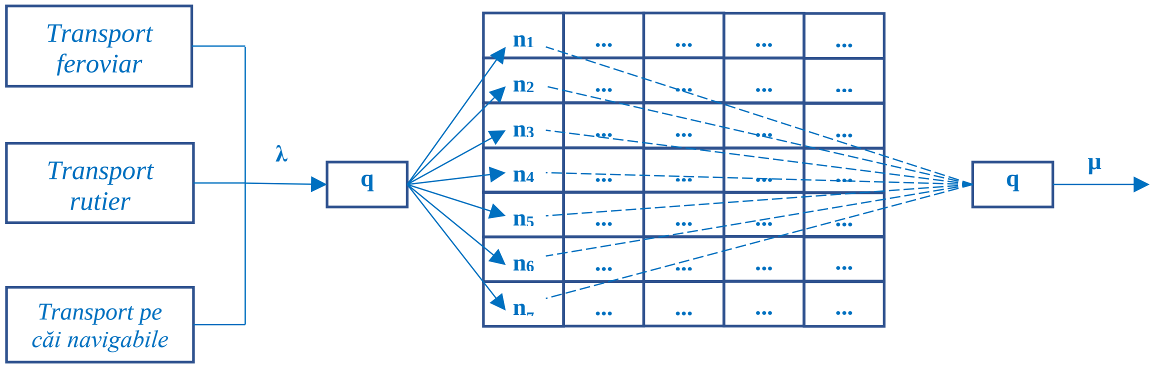


Figure 2.2. Warehouse representation as a queuing system (Source : adapted after (Raicu and Costescu, 2006))

2.2.1.3. Facilities for loading in transport means

2.2.1.3.1. Level harmonziation

It is necessary to distinguish between the notions of maximum capacity and actual capacity. In the case of maximum capacity, the existing transit and processing capacity of the terminal can be distinguished. For example, if we refer to the case of the rail transport network with consolidation terminals (technical or sorting stations), the transit and processing capacity is expressed by the maximum number of freight trains (or wagons) that can pass through, as well as by the maximum number of trains (or wagons) that can be processed in 24 hours (Tomescu, 1966).

The notion of effective capacity defines the total volume of activity that the terminal performs over a long period of time taking into account both the traffic structure and the qualitative indicators of the activity. The fulfillment of the qualitative indicators of the transport activity and of the terminal, as well as of the stability between the arrivals and the shipments in / from the terminal can be ensured only if the demand of the installations and equipment exceeds the level of the effective capacity. The actual capacity is always lower compared to the maximum (Raicu and Maşală, 1981). This correlation between the required, effective and maximum capacities of a terminal and its tasks over a period of time is illustrated in Figure 2.5.

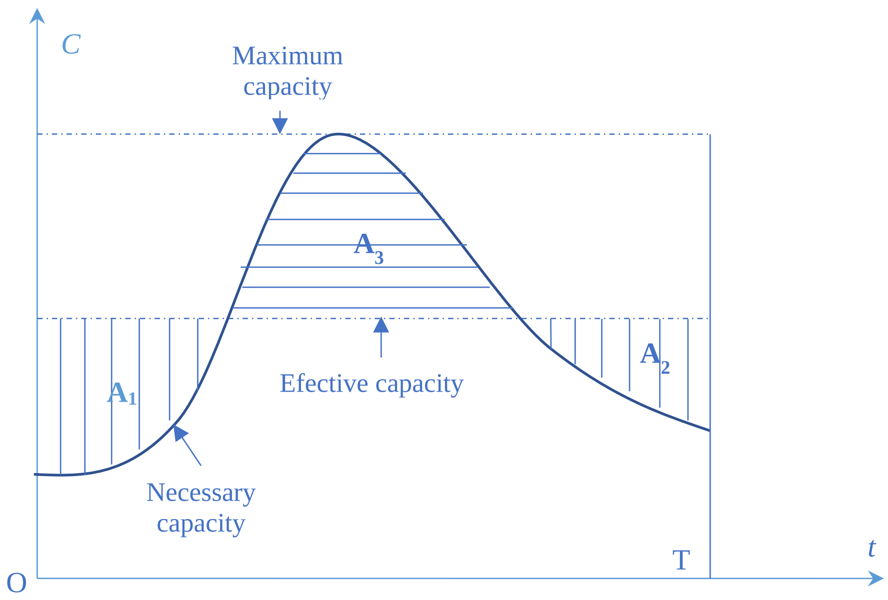


Figura 2.5. Relationship between necessary and effective capacity during an anlaysis period (Source : (Raicu and Maşală, 1981))

2.2.1.3.2. Probablistic model for determing number of equipments

The objective function of the problem of determining the need for goods handling equipment is:

$$\min F = \min\left(e_{mf}\Phi_{mf} + e_a\Phi_a + e_r\Phi_r + e_{mf}{}'\Psi_{mf} + e_{ast}\Psi_{ast}\right) \qquad (2.1)$$

where Φ_{mf}, Φ_a, Φ_r represent the actual working hours, idle times with service personnel, respectively without equipment service personnel during a year;

Ψ_{mf}, Ψ_{ast} - the idle times of the means of transport at the loading / unloading operations, respectively of waiting in order to start these operations during a year.

Time elements are determined by the following relationships (Raicu and Maşală, 1981):

$$\Phi_{mf} = N \cdot b_m = \frac{\lambda T}{\mu} \qquad (2.2.a)$$

$$\Phi_a = NT - \Phi_{mf} = \frac{(n\mu - \lambda)T}{\mu} \qquad (2.2.b)$$

$$\Phi_r = n(8760 - T) \qquad (2.2.c)$$

$$\Psi_{mf} \cong \Phi_{mf} = \frac{\lambda T}{\mu} \qquad (2.2.d)$$

$$\Psi_{ast} = N \cdot \frac{1}{\mu} \cdot (\mu \cdot \bar{t}_{astep}) \qquad (2.2.d)$$

2.2.1.4. Activity technologies for handling platforms

In the activity from the handling fronts, all the equipment / installations used fulfill distinct roles in the transit of the demand through the system. When modeling the service of requests according to a specific technology, one notices the existence of some equipment that can temporarily store and others that cannot fulfill this function (Raicu, 2007). In the case of activity in railway terminals, it is necessary to identify and correlate the processes included in the processing technologies of the different groups of wagons. In the case of loaded wagons arriving, before their arrival, the transit office shall notify (on the basis of the information received) the recipients of the goods and prepare the fronts for handling and the means of handling the goods. After the arrival of the wagons, they will be introduced to the handling fronts according to a pre-established schedule and will be subjected to single or double operations, as the case may be.

If we refer to the technology of the activity of processing empty arrived wagons, first a maneuver plan will be drawn up for the introduction of wagons at the handling platforms arranging that in parallel any wagons found during loading to be removed from the fronts. At the time of scheduling, the transit office shall notify the consignors of the goods, communicating the number of wagons arriving and the categories of goods which may be loaded on them. Once the wagons arrive at the station, they are checked to see if they can be loaded into that category. If loads are loaded on several fronts, the wagons are chosen first and then inserted at the fronts. The aim is to make the train easier, by removing the wagons after loading in a predefined order.

2.2.2. Investment strategies to increase the performance of transport entities formation

The main objective of the problem is to minimize the calculation expression of an optimization criterion C_{ik}, taking into account all the elements of expenses that are dependent on the value of the existing resources in the year *i* at the handling platform *k*. The value of the optimization criterion C_{ik} is given by relationship :

$$\begin{aligned} C_{ik}(I_{ik}) &= \sum_{i=1}^{m}\sum_{k=1}^{2} C_{ik}(I_i, I_{ik}) = (a_1 - a_2)(I_{11} + I_{21} + \ldots + I_{m1}) + \\ &+ a_2\left[mI_1 + (m-1)I_2 + \ldots + I_m\right] + e_1 \cdot V_1\left(\frac{Q_{11}^2}{I_{11}\cdot r_{11}\cdot \eta_{11}} + \ldots + \frac{Q_{m1}^2}{I_{m1}\cdot r_{m1}\cdot \eta_{m1}}\right) + \\ &+ e_2 \cdot V_2\left[\frac{Q_{12}^2}{(I_1 - I_{11})\cdot r_{12}\cdot \eta_{12}} + \frac{Q_{22}^2}{(I_1 + I_2 - I_{21})\cdot r_{22}\cdot \eta_{22}} + \ldots + \right. \\ &\left. + \frac{Q_{m2}^2}{\left(\sum_{i=1}^{m} I_i - I_{m1}\right)\cdot r_{m2}\cdot \eta_{m2}}\right]. \end{aligned} \tag{2.4}$$

where :

a_k este annual rate of return on investment for type equipment *k*;

e_k - the equivalent value of idle hour wagon per tonne of freight loaded in the wagon ;

r_{ik} - the number of daily rounds in which the wagons of year*i* at handling platform *k*;

η_{ik} - operating productivity achieved in the year *i* and by the machines at the handling front *k*.

The conditions that must be imposed on the problem are the following:

$$\sum_{i=1}^{m} I_i \leq I \tag{2.5.a}$$

$$I_{0i1} \leq I_{i1} \leq \sum_{i=1}^{m} I_i - I_{0i2} \tag{2.5.b}$$

$$\begin{cases} I_{011} + I_{012} \leq I_1 \leq I \\ 0 \leq I_2 \leq I - \left(I_{011} + I_{012}\right) \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ 0 \leq I_m \leq I - \left(I_{0(i-1)1} + I_{0(i-1)2}\right) \end{cases} \tag{2.5.c}$$

unde I is total investment value allocated for the *m* years and for the *k* platforms;

I_{0ik} - the minimum amount of resources available in the year *i* and for handling the quantity of goods Q_{ik}.

Condition (2.6.a) requires that the investments made in each of these m years must not exceed the total value I of the investment allocated for those k handling fronts. The restriction (2.6.b) takes into account the need to ensure mechanized handling of the volumes of goods from each of the k handling fronts. The set of restrictions (2.6.c) aims to limit the investments that are made every year.

The value of parameter I_{0ik} is determined with relationship (Raicu and Maşală, 1981):

$$I_{0ik} = \frac{Q_{ik} \cdot V_k}{365 \cdot n_s \cdot t_s \cdot \eta_{ik} \cdot \tau_0} \tag{2.7}$$

where n_s este the number of shifts in which a front is worked;

t_s - shift duration (in hours);

τ_0 - working time utilization coefficient.

Therefore, the problem will be limited to setting the minimum value of the objective function (2.4) that satisfies the constraints (2.5.a) - (2.5.c). In order to identify the minimum optimization criterion, the projected gradient method will be used for solving (Stere and Roman, 2021). This method is used for objectively convex functions, both in the presence of linear and nonlinear constraints (Dancea, 1976). The logical scheme of the algorithm for the optimal distribution of resources for the endowment of the handling fronts in the consolidation terminals applying the projected gradient method is represented in figure 2.6.

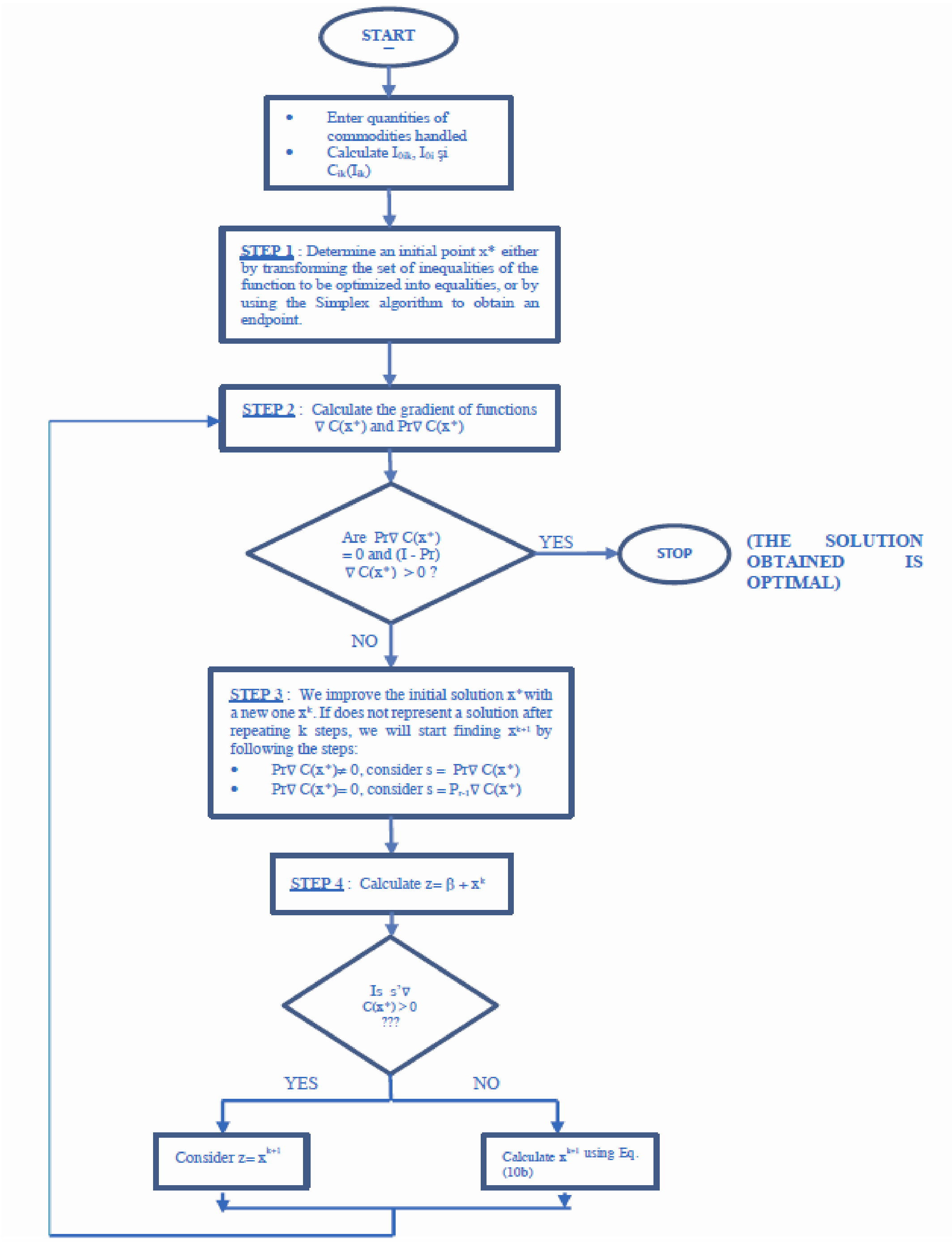


Figure 2.6. Logic scheme of the resource allocation model for equipping the handling fronts (Source : (Stere and Roman, 2021))

3. TRANSPORT ENTITIES FORMATION

3.1. Mathematical models for terminals location problem in networks with flows consolidation

3.1.1. Hub-and-spoke networks characteristics

In order to increase the efficiency of transports, it is resorted to the organization of services on networks with *hub-and-spoke* configurations (Costescu, 2010; Raicu et. All, 2011; Stîngă, 2018). The principle of these configurations has been used for many years in rail and air transport systems, but in recent decades, concerns for the configuration of these types of networks have intensified at different levels of operation (Stere, 2020). In systems where services are to be organized for a large number of origin-destination pairs, networkconfigurations with single-mode or intermodal flow consolidations are recommended (Figure 3.1).

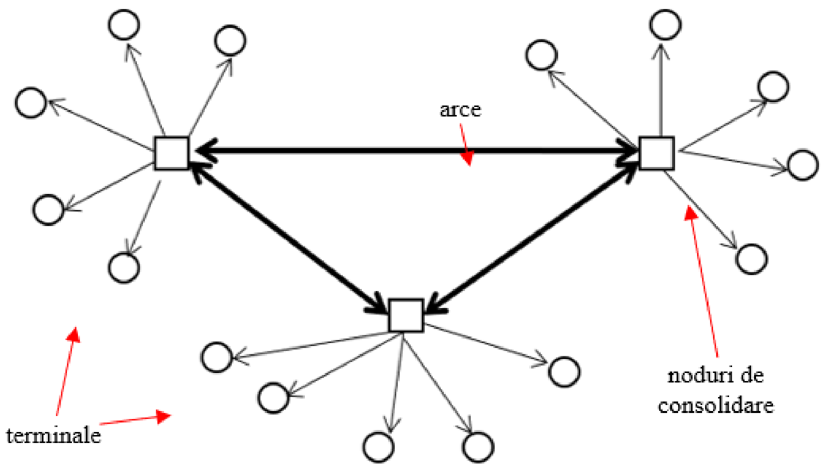


Figure 3.1. Schematic representation of a *hub-and-spoke* network

Direct connections are eliminated through networks with flows consolidation for which transport demand is insufficient to ensure efficient service. In the case of such a configuration, the direct relations between two terminals are maintained only if the demand is sufficient to justify the service (Schönemann, 2016). In one area, the generated streams that are in small quantities and have different destinations are routed to a central terminal (*hub*). Here they are broken down by area of destination and consolidated with other flows of goods which have the same destination or whose route has a common trunk. The flow consolidation network model creates opportunities to diversify and improve the quality of transport services. There are a number of benefits by using these transportation networks (Bontekoning, 2006; Rodrigue et al., 2020):

- Obtaining *the returns of scale* both on the itineraries within the network and at the level of the hub nodes.
- Achieving *economies of density*, given by a higher frequency of transport services (Jara-Diaz et. All, 2013).

Transport networks with flow consolidations also have a number of disadvantages, mainly due to the fragmentation of transport processes and the need for transfers / processing in consolidation terminals, with effects on increasing durations and costs. The performance of a *hub-and-spoke* network depends not only on the functions of the hub terminal, but also on its location (Kreutzberger and Konings, 2016). In order to optimize the process of setting up traffic entities, it is important both to know the positions of the nodes in the entire railway network where they can be set up and to identify the main methods to choose the optimal solution for setting up these traffic entities.

3.1.2. K – hub terminals location problem

The formulation of this problem was made by O'Kelly in 1987, the objective function for the location of k terminals aiming to minimize the total transfer costs (Farahani et al., 2013). It is assumed that there are three categories of transfer costs, namely (Zabihi and Gharakhani, 2018):

- goods transfer cost from the origin terminal to the *hub* terminal (c_{il});
- goods transfer cost between *hub* terminal (c_{lm});
- goods transfer cost from *hub* terminalul to destination terminal (c_{jm}).

The following notations are used to define the objective function:

w_{ij} - flow from origin node *i* to destination *j*;

Y_{ij} - binary decision variable equal to 1 if node *i* is allocated to a *hub* placed in point j and 0 otherwise ;

X_j - binary decision variable equal to 1 if node *j* is *hub* and 0 otherwise.

α – subunit parameter that applied to reduce the transfer cost between two hub terminals due to scale efficiency.

The objective function of the k-terminal location problem is (O'Kelly, 1987):

$$\min\left(\sum_i\sum_l Y_{il}c_{il}\left(\sum_j w_{ij}\right)+\sum_j\sum_m Y_{jm}c_{jm}\left(\sum_i w_{ij}\right)+\alpha\sum_i\sum_j\sum_l\sum_m w_{ij}c_{lm}X_lX_m\right) \quad (3.1)$$

with following restrictions:

$$\sum_j Y_{ij}=1 \quad (3.2)$$

$$\sum_j X_j=k \quad (3.3)$$

Relationship (3.1) is the objective function that aims to minimize the transfer cost between network nodes. In this expression, the first term defines the cost of transferring the outflow from node i to node *hub* j. The second term represents the cost of transferring the input flow from *hub* node m to service node j, while the last term represents the transfer cost between *hub* nodes l and m. Restriction (3.2) requires that the transport flow from each a node that does not perform the *hub* function is assigned to one of the k *hub* nodes, and the constraint (3.3) ensures that the number of *hub* nodes is equal with k.

3.1.3. Median problem

In order to model a network of hub terminals, it is necessary to go through the following steps (Raicu et al., 2011) :

- determing the optimal location of *hub* terminal;
- allocation of origin and destination points of *hub* terminals;
- identyfing the routes between *hub* terminal
- affecting the flows on *hub – and – spoke* network.

It is found that the solutions of the four steps listed above are dependent on each other. Practically, however, in order to allow a mathematical solution as easy as possible, a sequential treatment is recommended and simplifications are used. A commonly used assumption is that the value of the transport cost is independent of the volume of the transport flow. Under these conditions, the unit cost for the route between two nodes denoted i and j (which are not *hub* terminals) that includes *hub* terminals l and m is (Farahani and Hekmaftar, 2009; Farahani et al., 2013):

$$c_{ij}^{lm} = \chi \cdot c_{il} + \alpha \cdot c_{lm} + \delta \cdot c_{lj} \tag{3.4}$$

where $c_{ij,}$ is the unit cost for the route between the two nodes *i* and *j*;
c_{lm} - the unit cost for the route between *hub* terminals *l* and *m*;
χ - coefficient of costs variation on the collection routes;
α - the cost reduction coefficient on the route between *hub* terminals;
δ - coefficient of costs variation on the distribution route (usually, its value is equal to 1).

The following binary decision variables are considered for choosing the optimal position of the terminals:

Z_{ij}^{lm} - variable equal to 1 if the flow between *i* şi *j* includes potential points for *hub* terminal *l* and *m* location and 0 otherwise ;

Y_l - variable equal to 1 if in node *l* a terminal *hub* is located and 0 otherwise.

Taking into account the notations listed above, the objective function for minimizing the total transport cost is (Costescu, 2010; Farahani et al., 2013):

$$\min \sum_i \sum_j \sum_l \sum_m c_{ij}^{lm} \cdot w_{ij} \cdot Z_{ij}^{lm} \tag{3.5}$$

with restrictions:

$$\sum_l Y_l = k \tag{3.6}$$

$$\sum_l \sum_m Z_{ij}^{lm} = 1 \tag{3.7}$$

$$Z_{ij}^{lm} \leq \mathrm{Y_l}, \ \forall i, j, l, m \in N \tag{3.8}$$

$$Z_{ij}^{lm} \leq \mathrm{Y_m}, \ \forall i, j, l, m \in N \tag{3.9}$$

$$Z_{ij}^{lm} \geq 0 \quad \forall i, j, l, m \in N \tag{3.10}$$

The objective function (3.5) is to minimize the total transport cost. The number of *hub* terminals (equal to k) is checked by the constraint (3.6). Condition (3.7) shows that each origin-destination pair (i, j) is assigned to a relation of *hub* terminals (l, m). Assuming that the origin-destination pairs (i, j) are rounded to a single *hub* node, then l = m. Restrictions (3.8) - (3.10) ensure that nodes l and m must first be selected as *hub* terminals, and only later is the flow allocated from node i to node j.

3.1.4. Coverage problem

In the case of this category of problems, it is assumed that each pair of home nodes is located at a predefined distance (the maximum value accepted from the service point of view) from the *hub* nodes, thus being considered covered. The transport cost from origin and destination j through the nodes of the selected *hub* less than or equal to a predetermined value is also considered. φ_{ij} ($c_{ij}^{lm} \leq \varphi_{ij}$). Therefore, the cost of locating terminal *hub* în node *l* must be taken into account, noted with F_l. Term φ_{ij} represents the maximum cost for covering terminals *i* și *j* while term V_{ij}^{lm} represents a binary decision variable equal with 1 if *hub* nodes located in nodes *l* and *m* are included on route (*i, j*) and 0 on the contrary.

3.2. Railway transport networks configuration

The transport network is a complex system composed of numerous elements with certain functions in the transport process (Raicu, 2007). In order to formalize the railway network in order to model the establishment of traffic entities, it is necessary to structure the data for the description of arcs and nodes, to identify the stations that delimit the administrative division of the railway network and the main functions provided (Figure 3.2).

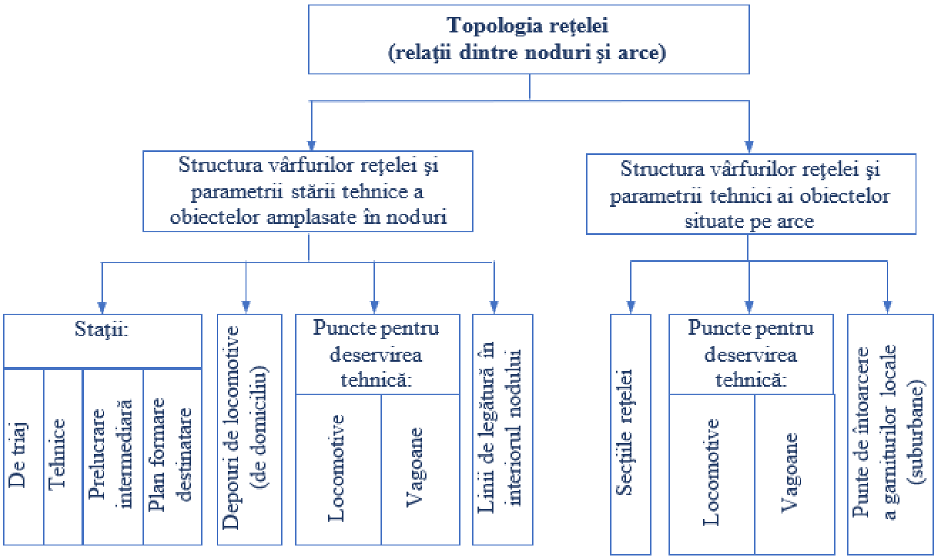


Figure 3.2. Information structure for formalizing the state of the railway network
(Source : adapted after (Raicu, 2007))

The nodes of the railway network in which the traffic entities are set up are the technical, triage and intermediate processing stations. These are, in fact, the sectioning points of a railway transport network that are equipped with constructions and installations with the help of which the freight train processing operations are carried out (Dragu, 2010). Figure 3.3 shows the stations of the Romanian railway network that perform the functions mentioned above.

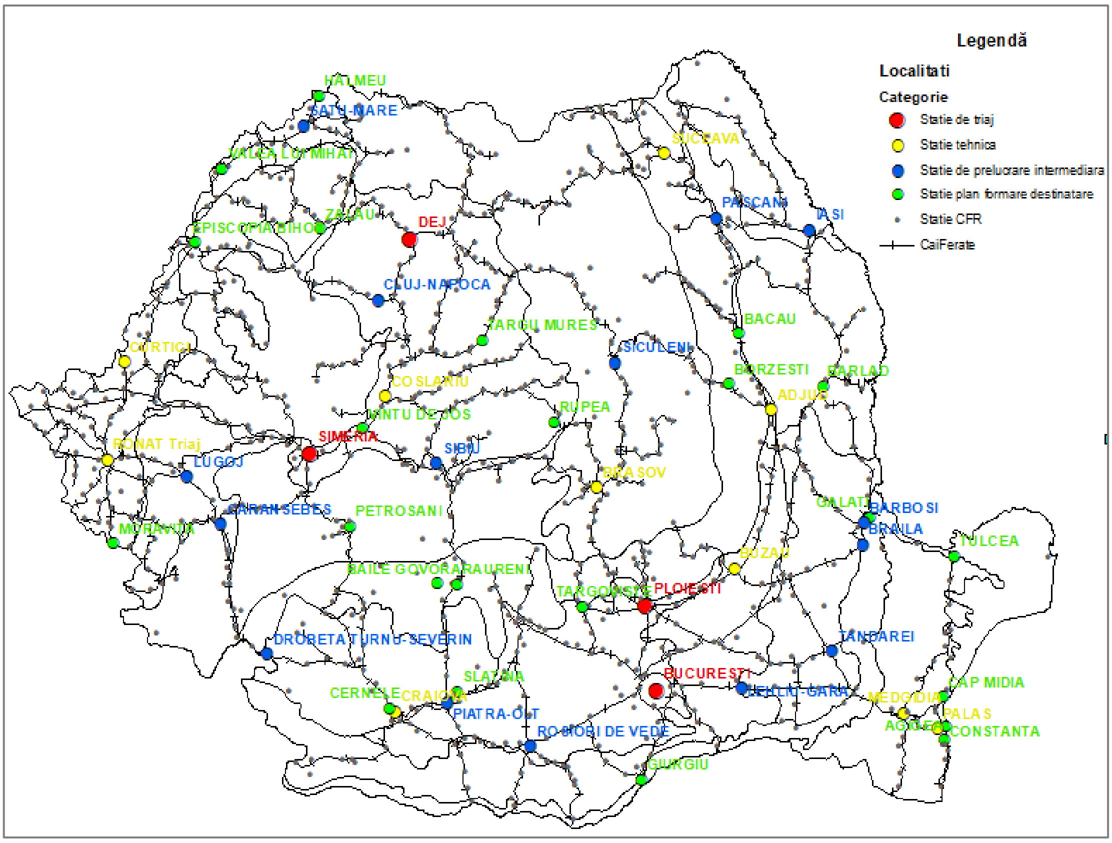


Figure 3.3. Technical stations, shunting yards, intermediate processing and formation plan for the Romanian railway network (Source : (Stere, 2020))

3.3. Determing the parameters characteristics of the consolidation of traffic entities

The formation and consolidation of traffic entities, their decomposition and the transfer of goods to the consignee requires a succession of processes in the transport terminals. The shuntig yards can be assimilated with a system that provides technological chains that connect the inbound traffic sections, the arrival group (group A), the hump in a gravity yard, the classification group, the shunting neck for formation, the departure group and the sections output traffic (figure 3.4).

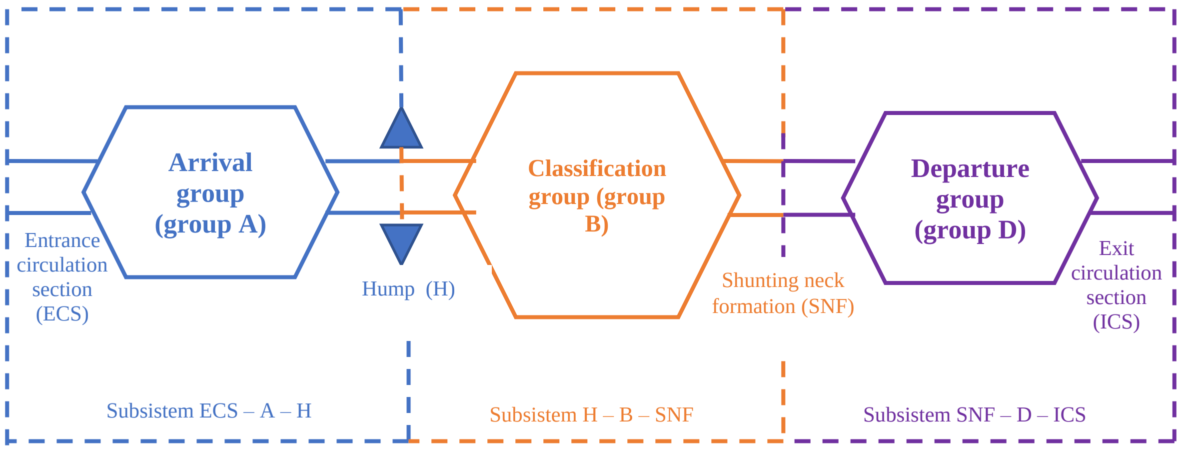


Figure 3.4. Component subsystems of a shunting yard

Based on the components and technological processes for which they are intended (train reception, shuntinh, train composition, dispatch), the sorting station can be structured as a complex mass serving system, in which the elements are grouped according to the types of operations (waiting, carrying out operations, accumulation) (figure 3.5):

- *G: Demand generators* within the system lead to the process of occupying the waiting places and determine the characteristics of the input flows.
- *W: Waiting points for demand* they are represented by elements in which the waiting times in order to carry out the different processes are recorded.
- *SS: Service stations* have a role in ensuring the continuity of the service / transit process of the traffic entities.
- *E: Exit points from the system* are elements „fueled” by service stations, waiting areas and, in some cases, even demand generators..

The multitude of direct and inverse relationships between the elements (figure 3.6) reveals the high degree of complexity required to model such a structure. The main objective of the modeling is to harmonize the activities of the component elements in order to obtain rational demands in given operating conditions. Due to the complexity of modeling the consolidation terminals of the traffic entities in which it is necessary to integrate the main factors that intervene in the operating costs, we resort to simplifying hypotheses and to the breakdown on different service regimes. In the case of modeling railway terminals with flow consolidations (technical and sorting stations), it is recommended to formalize them as *“waterfall”* mass serving systems.

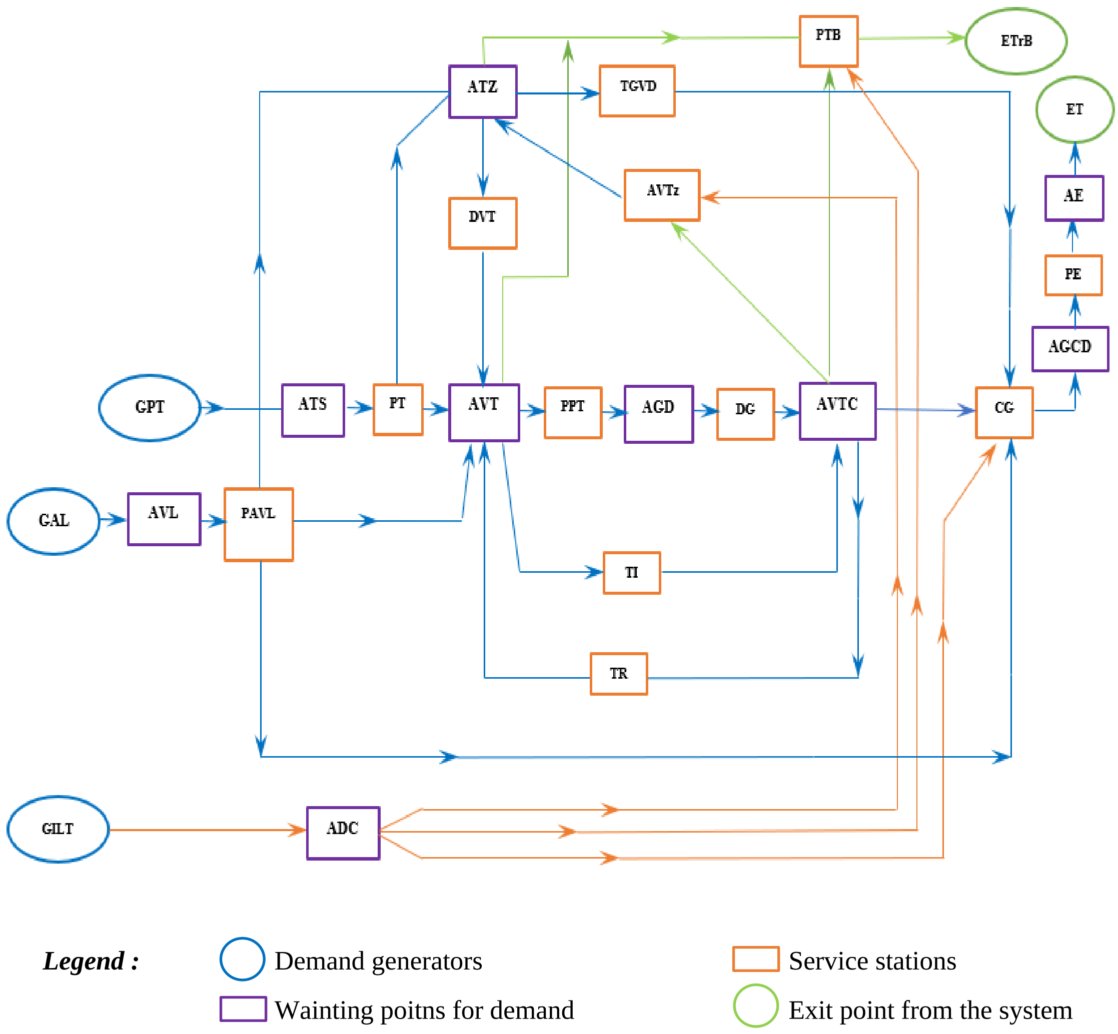


Figura 3.5. Complex mass-serving system of a consolidating railway terminal (shunting yard)

The total time that a request is found in systems with "*waterfall*" service stations is calculated as follows:

$$t_{med} = \sum_{i=1}^{f} t_{sv,i} + \sum_{i=1}^{f} t_{a,i} \tag{3.9}$$

where: $t_{sv,i}$ is average serving time for each phase i of serving;

$t_{a,i}$ - average waiting time in the phase i;

f - the number of phases in which the service is decomposed.

From the above presentation, it is observed that one of the processes that influences the formation of traffic entities in shunting yards is the accumulation of wagons. This process starts when the first group of wagons with a specified destination arrives from the station and ends when the last group that has the same destination is mentioned when it arrives at the station, from the adjacent sections or from its own loads.It is necessary to consider in the calculations the following expression of wagon consumption - hours for storage that takes into account the size of the set of carriages and the storage parameter:

$$\Omega = c \cdot m \tag{3.10}$$

where c is denoted by the accumulation parameter and the term m represents the size of the wagon group. *Accumulation parameter* is an indicator that characterizes the process of accumulation of a set of wagons. The expression of the accumulation parameter is given by the relation:

$$c = 0,5 \cdot T_{ac} \cdot \left(1 - \frac{n_{tr,exped}}{n_{tr,sos} \cdot \gamma}\right) = 12 \cdot \left(1 - \frac{n_{tr,exped}}{n_{tr,sos} \cdot \gamma}\right) \tag{3.11}$$

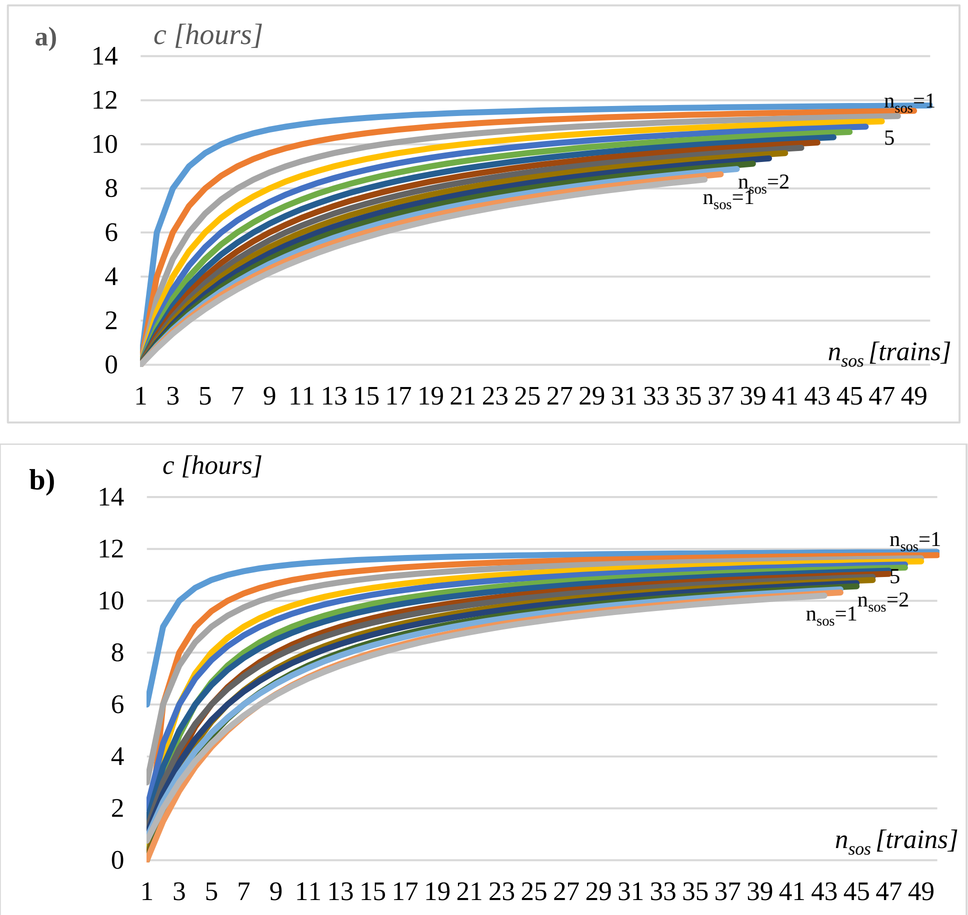


Figura 3.6. Variation of the accumulation parameter in relation to the number of arriving trains (n_{sos}) and the number of trains after which no wagons remain on the assigned destination line $\gamma = 1$ (a) and $\gamma = 2$ (b) (Source: (Stere, 2021))

Based on this relationship, the variation of the accumulation parameter will be analyzed for a number of trains that were dispatched between 1 and 15 and for values of the parameter corresponding to the frequency of interruptions occurred during the accumulation process equal to 1 and 2 (figure 3.6). From this figure it is easily observed that the accumulation parameter decreases simultaneously with the increase of the current of wagons to be shipped for the same values of $n_{tr,\exp ed}$. Also, the accumulation parameter tends to decrease as the number $n_{tr,sos}$ of trains arriving at the station containing wagons for a specific destination as well as an increase due to the increase in the value of the parameter γ.

3.4. Consolidation systems of transport flows into traffic flows

3.4.1. Run-through trains

The *run-trough* trains defines the category consisting of wagons which are loaded in a single station by one or more consignors for certain stations of destination, for one or more consignees, without undergoing any maneuvering or processing during the journey (it can be classified as run-trough trains with wagons having the same consignee or consignor respectively). The formation of traffic entities in run-trough trains (component of the process of setting up railway traffic entities) implies (Săndulescu, 1965):

- Determining the currents of loaded or empty wagons ready to be shipped from the places of loading to their places of destination;
- Description of the technical endowments of the technical and shunting yards, as well as their loading-unloading capacities;
- Defining the loading and unloading programs of the trains departed at the stations of origin and those of destination;
- Planning the technological processes for the formation of the *run – through* trains running in the origin stations and coordinating the handling operations (loading-unloading);
- Analysis of the indicators of the training activities of the trains in the main technical stations of the railways.

3.4.2. Block trains

Block train is the train consisting of wagons accumulated in a technical, shunting yard or disposal station which has as its destination for decomposition another technical station and which runs in transit without maneuvering and processing through one or more technical stations. The common feature of run-through and block trains is that they are formed at loading stations, transit through one or two technical stations without handling and processing, and are unloaded at one or more destination stations.

It is found that the movement of wagons in the composition of run – trough trains, in transit through the technical stations of the railway network, gives time savings for each wagon. This value shall be determined for each individual technical station and shall take into account both the time rules laid down for carrying out technological operations on the wagons and the train running schedule. If we relate this economy to a single wagon in the composition of the freight train, we have:

$$t_{ec} = t_{prel} - t_{tranz} - t_{ac} \qquad (3.12)$$

It should be noted that the size of the parameter t_{ac} shall be determined in accordance with the rules of the technological work processes of the shunting yard, without taking into account the wagons stadstiil time that are pending the dispatch of the train in accordance with the traffic schedule. Thus, the wagons idle time in technical stations is calculated with a relation that takes into account the size of the current of processed wagons and the consumption of wagons - accumulation hours. Mathematically, the expression is written like this:

$$\sum t_{teh} = \sum N_{pr} \cdot t_{ec} + \sum k \cdot c \cdot m \qquad (3.13)$$

in which term $\sum t_{teh}$ represents the part of the wagons - stationary hours that vary depending on the way railway traffic entities are formed.

Another element with a direct influence on the comparison of the options for the formation of railway traffic entities is the processing equivalent. It allows the equivalence of wagons - processing hours into wagons - idle hours, being a quantity that characterizes the efficiency of the processing activity in a certain station. If in relation (3.13) the size of the processing equivalent r is also taken into account, we will obtain the final expression of the consumption of wagons - stationary hours equivalent for parking in the technical stations of the railway network (Stere, 2021):

$$\sum t'_{teh} = \sum N_{pr} \cdot \left(t_{ec} + r\right) + \sum k \cdot c \cdot m \tag{3.14}$$

Figure 3.7 shows the variation of the relations (3.13) and (3.14) for different ways of organizing the wagon currents as a consequence of the variations of the terms $\sum N_{pr} \cdot t_{ec}$ and $\sum N_{pr} \cdot \left(t_{ec} + r\right)$ depending on the number of wagons processed in the technical and shunting yards. After analyzing the graphic representation, it is observed that there is a value of the number of processed wagons which corresponds to a minimum of the two functions. Specifically, there is a variant of forming railway traffic entities (which is considered optimal) which gives a minimum idle time for wagons in the technical stations of the railway network. Therefore, a careful organization of the wagon currents achieves an acceleration of the wagon 's turnover.

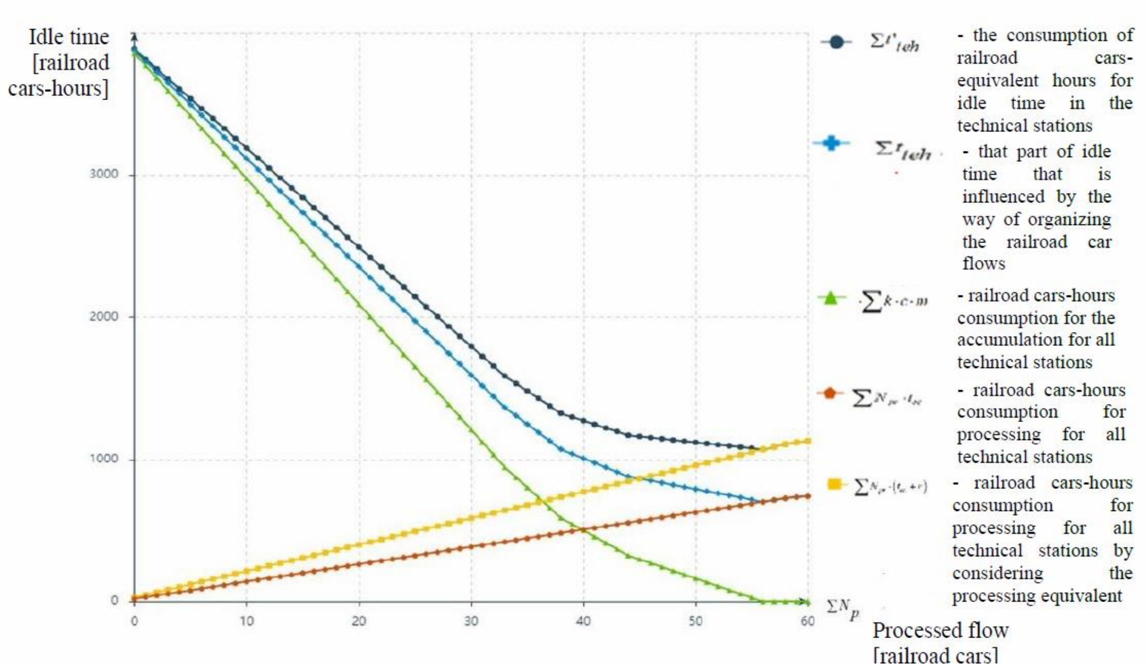


Figure 3.7. Variations of fuctions Σt_{teh} and $\Sigma t'_{teh}$ depending on the parameter ΣN_{pr} (Source: (Stere, 2021))

Therefore, for a better organization of rail freight transport, it is necessary to set up traffic entities by developing a train formation plan that aims at the rational allocation of sorting operations between shunting yards in close accordance with their technical equipment (Francu and Raicu, 1986; Butko et al., 2017). The establishment of traffic entities, through the freight train formation plan, is one of the most important areas of research in rail transport planning

(Yaghini et al., 2013; Yaghini et al., 2014) because identifying the optimal option is a task. difficult to solve.

3.5. Mathematical models for traffic entities formation

3.5.1 Mathematical models for monogroup trains formation

3.5.1.1. Absolute calculation method

Identifying the optimal way to form railway traffic entities by using the absolute calculation method involves, in essence, the calculation of indicators for each option. In order to identify the optimal variant, all those railway traffic flows (except those section currents) that meet the requirement will be examined:

$$N_{vg} \cdot \sum t_{ec} \geq cm \qquad (3.15)$$

where N_{vg} represents the current of wagons from a station of origin to a station of destination and term $\sum t_{ec}$ refers to a sum of the time savings due to the transit of freight trains through the technical stations along the way. In case flow N_{vg} does not meet this condition, it is checked whether its combination with neighboring rail traffic flows complies with this condition. If the combination (3.15) is not fulfilled either, the respective wagon current will not be taken into account in future calculations.

If the requirement is met, it will move to the combined consolidation option that satisfied the relationship (3.15). For the optimal option of setting up the railway traffic entities, the option will be chosen in which the number of wagons - hours has the minimum value and which ensures at the same time a more uniform distribution of sorting tasks between sorting stations in close accordance with their technical equipment. The logic scheme of the algorithm for identifying the variant of forming monogroup traffic railway entities by applying the method of absolute calculation is illustrated in figure 3.8.

If the number of technical stations is equal to five, the analysis of the possibilities for consolidating rail traffic flows will be carried out directly. After calculating the wagon consumption - hours equivalent for each of the five basic technical stations, three variants with minimum wagon consumption - hours and with the characteristics corresponding to the best options for consolidating the railway transport flows are identified. If the number of technical stations is equal to six, it is necessary to calculate the additional consumption of wagons - equivalent hours (as a result of the appearance of the sixth station) for a number of 74 groups of variants for the first basic technical station. Then the 103 variants of consolidating the railway traffic flows for the five technical stations on the considered highway are determined (starting from the second and ending with the sixth).

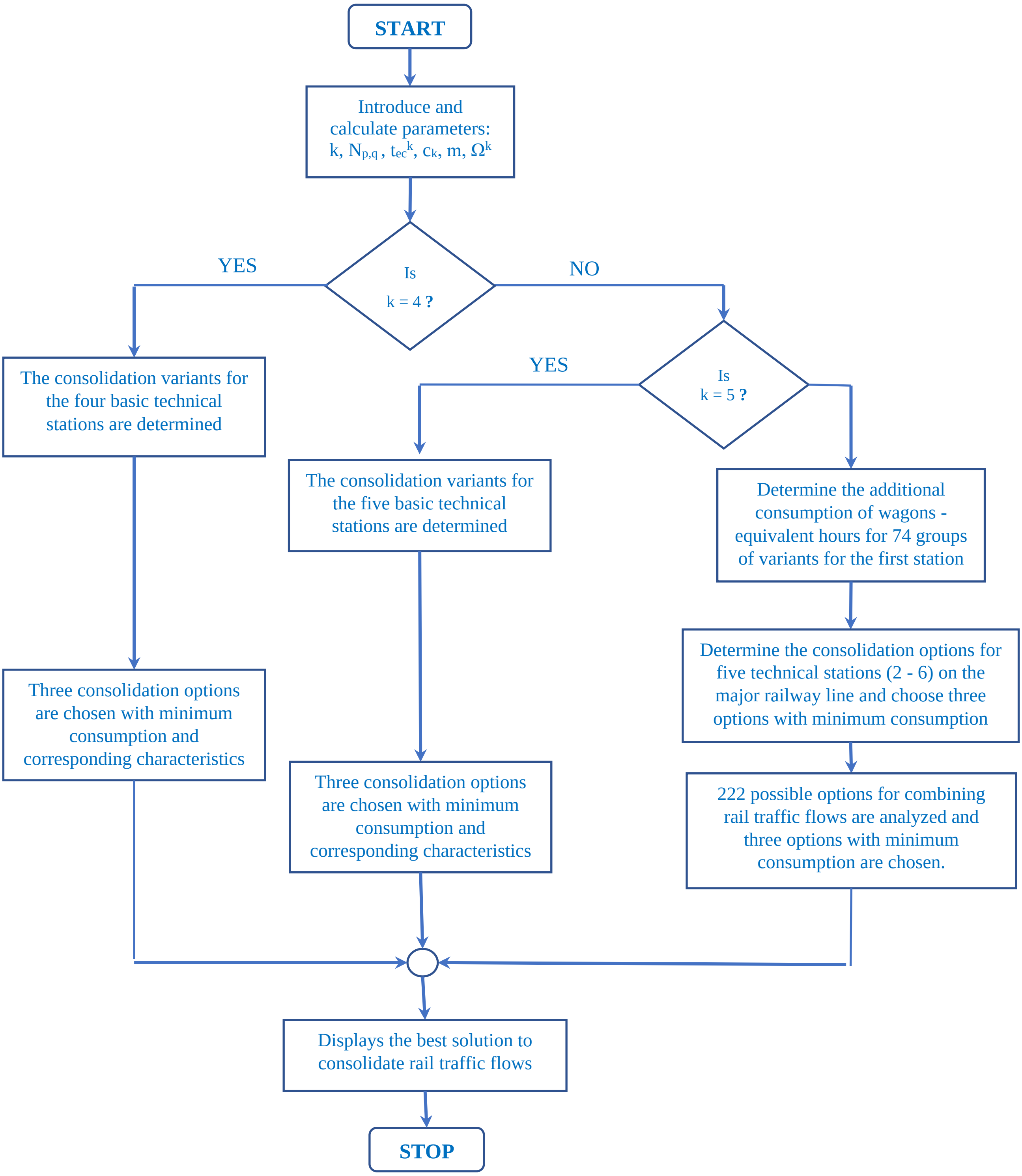


Figure 3.8. Logical scheme of the algorithm for forming up single-group traffic railway entities using the absolute calculation method

3.5.1.2. Analytical comparisons method

The conjugate analytical comparisons method is based on the principle of gradually choosing the most advantageous relationships, in other words, eliminating inefficient relationships. The effect of this procedure is that the number of possible relationships for trains with a single group is much smaller compared to the number of possible variants of the training plan. The examination of the different relationships containing a number of wagon flows can be done either on the basis of sufficiency condition:

$$N_{vg} \cdot \sum t_{urm} \geq cm \tag{3.16}$$

either on the basis of the necessity requirement based on relationship (3.15). În inequality (3.16), term $\sum t_{urm}$ sum of time savings due to the transit without remaking freight trains through the technical stations along the route. Compliance with the condition of adequacy ensures the separation of the currents of wagons taken into account in the optimal option of setting up the railway traffic entities, each current having an independent destination.

Assuming that only a current of wagons meets the requirement, it is necessary to check whether it is economically appropriate to combine it with another current which in turn fulfills this condition and is in the same station (or in -one nearby). In the optimal variant, the wagon currents are established for all technical and sorting stations that simultaneously satisfy the condition of sufficiency and necessity or only one of these conditions. If one wagon current does not meet either of the two conditions, it will combine with the other wagon currents.

3.5.1.3. Conjugate analytical comparisons method

This method is based on the principle of gradually choosing the most advantageous relationships, in other words, eliminating inefficient relationships. The effect of this procedure is that the number of possible connections for trains belonging to a single group is much smaller compared to the number of possible options for consolidating rail traffic flows.

As a first step, it will be checked which of the wagon bundles in the step diagram satisfies the condition of sufficiency $N_{vg} \cdot \sum t_{urm} \geq cm$. Assuming that the current of wagons meets this condition, it will be included in the optimal way of consolidating the railway traffic flows.

If only the necesity requirement is met, additional calculations are required to determine the maximum possible wagon economy - hours resulting from combining this current of wagons with another or others running either from the respective basic technical station or from the following technical stations on the itinerary.

In the second stage, it is identified which of the currents made up of several beams gives the most significant wagon savings - hours. In this choice, the condition that each beam between two basic technical stations must comply with the condition of sufficiency must be observed $N_{vg} \cdot \sum t_{urm} \geq cm$. Otherwise, the pair of origin - destination for a current of wagons will not be able to be included as an optimal option to consolidate the transport flows. Therefore, the next stream of wagons consisting of one or more bundles is switched on and the previous principle presented is applied again.

The algorithm for the formation of railway traffic entities by using the method of conjugate analytical comparisons presupposes the completion of the steps detailed in the logical scheme of the program illustrated in Figure 3.9.

The main advantage of the method of conjugate analytical comparisons is the possibility to analyze all the variants of setting up the railway traffic entities for a single destination, not being influenced by the number and location of the train forming stations. Also, the wagon bundles can be combined in all possible variants, starting both to the neighboring stations and to the others.

3.5.1.4. Th heuristic method

Another method of determining the optimal variant of the freight train formation plan in railway hub – and – spoke networks is the heuristic method. This method is based on the principle of wagon flows classification into four main categories: basic, additional, unifying and complementary wagon flows (Raicu, 1963). *The basic wagon flows* represent those wagon flows which, when transiting without processing through a technical station, provide an economy at least equal to the consumption of wagons – hours for a single destination. Mathematically, this condition can be written like this (Raicu, 1963; Stere and Olteanu, 2020):

$$N_{vg} \cdot t_{ec}^{k} \geq c \cdot m > N_{vg} \cdot t_{ec}^{\min} \tag{3.17}$$

The additional wagon flows are those flows for which the sum of wagons – economy hours resulting from the transit of technical stations along the considered network is greater than or equal to the value of wagon consumption – accumulation hours for a single destination. Mathematically, this inequality is of the form (Stere and Olteanu, 2020):

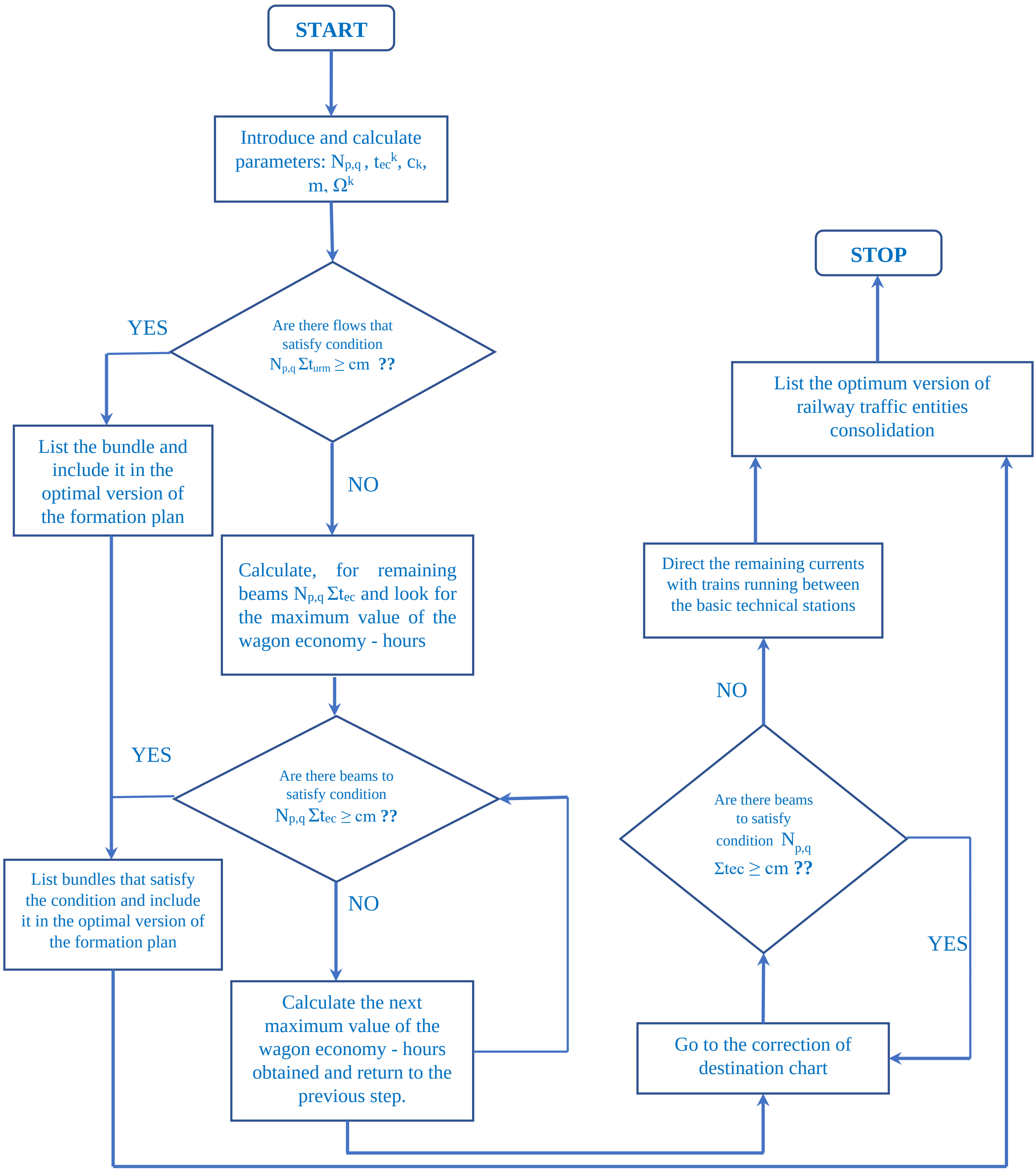


Figure 3.9. Logical scheme of the algorithm of the formation of monogroup railway railway entities using the conjugate analytical comparisons method

$$N_{vg} \cdot \sum t_{ec} \geq c \cdot m > N_{vg} \cdot t_{ec}^{\max} \qquad (3.18)$$

Through *unifying wagon flows* are defined as those wagon flows for which the economy obtained by their transit without processing through several technical stations is at least equal compared to wagons – accumulation hours while for each current separately it is always smaller. Mathematically, this condition can be written as follows (Stere and Olteanu, 2020):

$$\sum\left(N_{vg}\cdot\sum t_{ec}\right)\geq c\cdot m > N_{vg}^{\max}\cdot\sum t_{ec} \qquad (3.19)$$

Complementary wagon flows represent those flows whose sum of the economy of wagons – hours resulting from transit through all technical stations on the route is lower compared to the number of wagons – hours of accumulation. This category of currents should not be divided into destinations because their separation has no economic justification. This inequality is expressed in this way (Stere and Olteanu, 2020):

$$\sum\left(N_{vg}\cdot\sum t_{ec}\right) < c\cdot m > N_{vg}^{\max}\cdot\sum t_{ec} \qquad (3.20)$$

The logic scheme of the algorithm that allows the identification of the variant of forming monogroup traffic railway entities by applying the method of direct analytical calculation implies the completion of the steps illustrated in Figure 3.10.

The heuristic method for establishing the optimal option for the formation of traffic entities has the advantage of quickly identifying it in strict accordance with the processing possibilities of the technical or triage stations of the railway network. In the case of major railway lines with significant variations over time in the volumes transported, this method allows easy correction of the formation plan, accurately forming those wagon currents whose variations require changing the optimal option of forming railway traffic entities.

3.5.2. Mathematical models for multigroup trains formation

The term grouped freight train means that category of trains composed of a number of groups of wagons which run to certain stations of destination. Thus, if the train has only one group in its composition, it will be a *monogroup train*. If the train is composed of two or more groups of wagons (having different origins and destinations), then it is called *multigroup trains* (Xiao and Lin, 2016). The formation of multigroup trains involves the "gathering" of several wagons in groups of wagons and the service of two or more destinations. The order of the groups in such trains corresponds to the geographical positioning of the destinations (Belošević et. all, 2019).

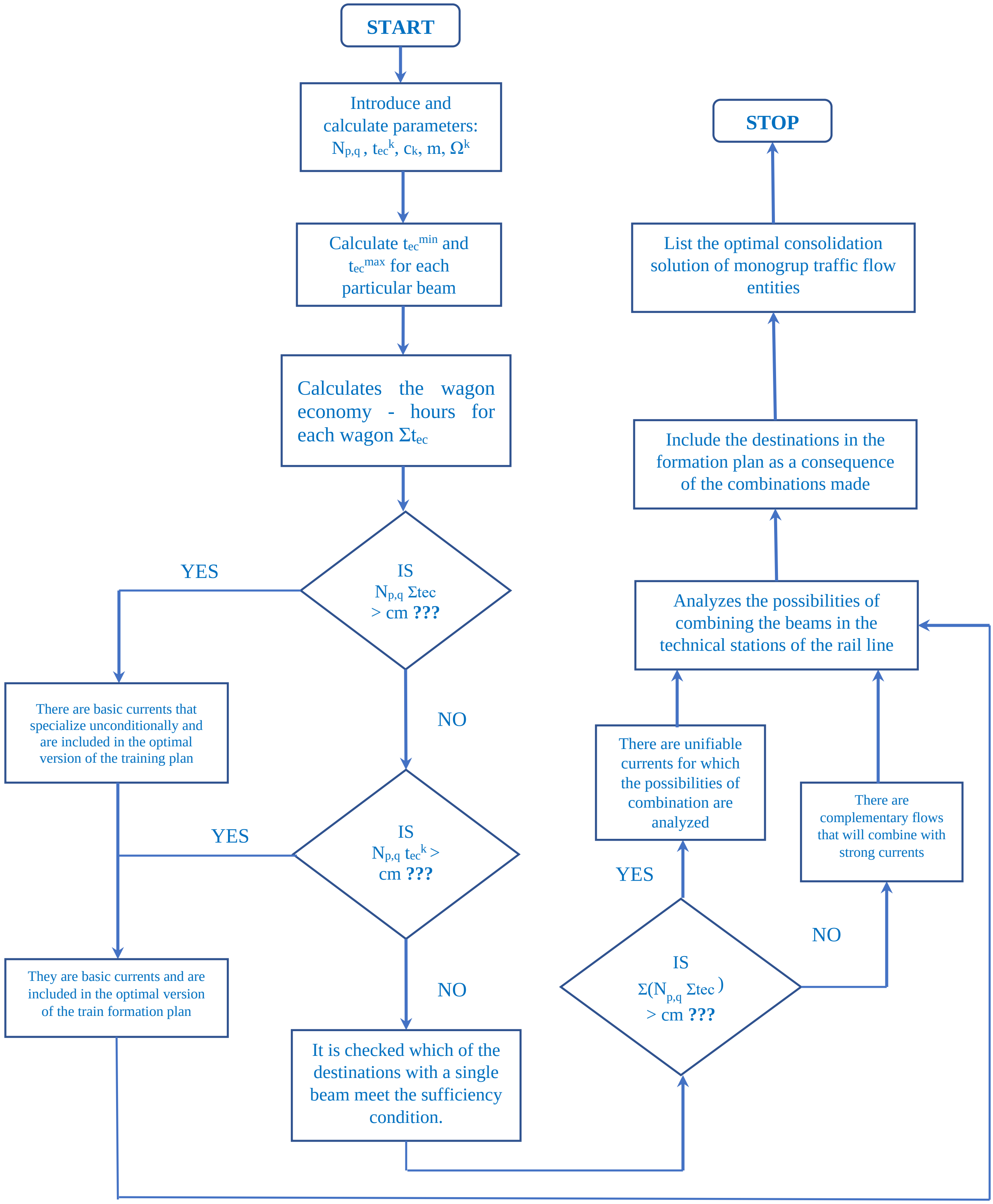


Figure 3.10. Logical scheme of the algorithm for the formation of monogroup railway railway entities by using the heuristic method

The main advantages of forming such trains are the reduction of wagons idle time and allows the concentration of shunting activity for a smaller number of marshalling yards (Ivić and Kosijer, 2012). Trains with a transport capacity used to the maximum on long common sections are also built, without all the wagons having the same destination (Troche, 2009). An algorithm that enables the formation of multigroup rail traffic entities should facilitate the determination of wagon consumption - hours for each variant of consolidation of monogroup trains. Subsequently, the options to be calculated must be chosen on the basis of the link between the number of wagons corresponding to each destination but also the calculation of the wagon consumption - hours of the chosen solutions. Then the first three options with the lowest consumption and the possibility of applying these solutions in practice will be chosen. Based on these observations, the logic scheme of this algorithm is illustrated in Figure 3.11.

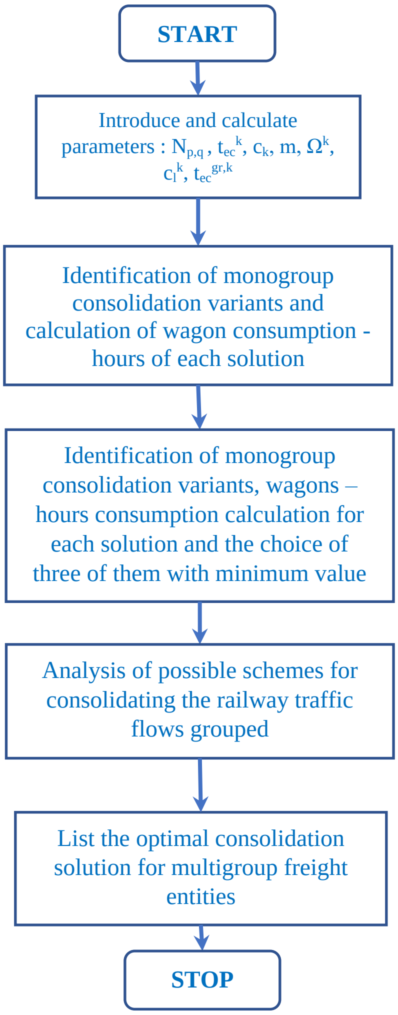


Figure 3.11. **Logic scheme of the algorithm for setting up grouped traffic entities (for multiple destinations)**

4. CASE STUDY

4.1. Interregional flows for major railway lines

The first step in choosing the ideal solution to form railway traffic entities is to establish the current of the wagons. More specifically, it is necessary to know those directions on the basis of which the trains are formed as well as the basic technical stations for each direction. An important condition is that the limits of the directions must coincide with the points of sudden change of wagon currents. When determining the wagon currents, the simplifying hypothesis will be considered according to which the wagon currents appear and go out in a few basic technical stations. We consider now the diagram of the railway network that will be used to exemplify the way in which railway traffic entities are set up (Figure 4.1). The border stations between the 4 considered railway lines (Lehliu - Gară, Videle and Orșova in this case) were marked in lower case (a, b, c).

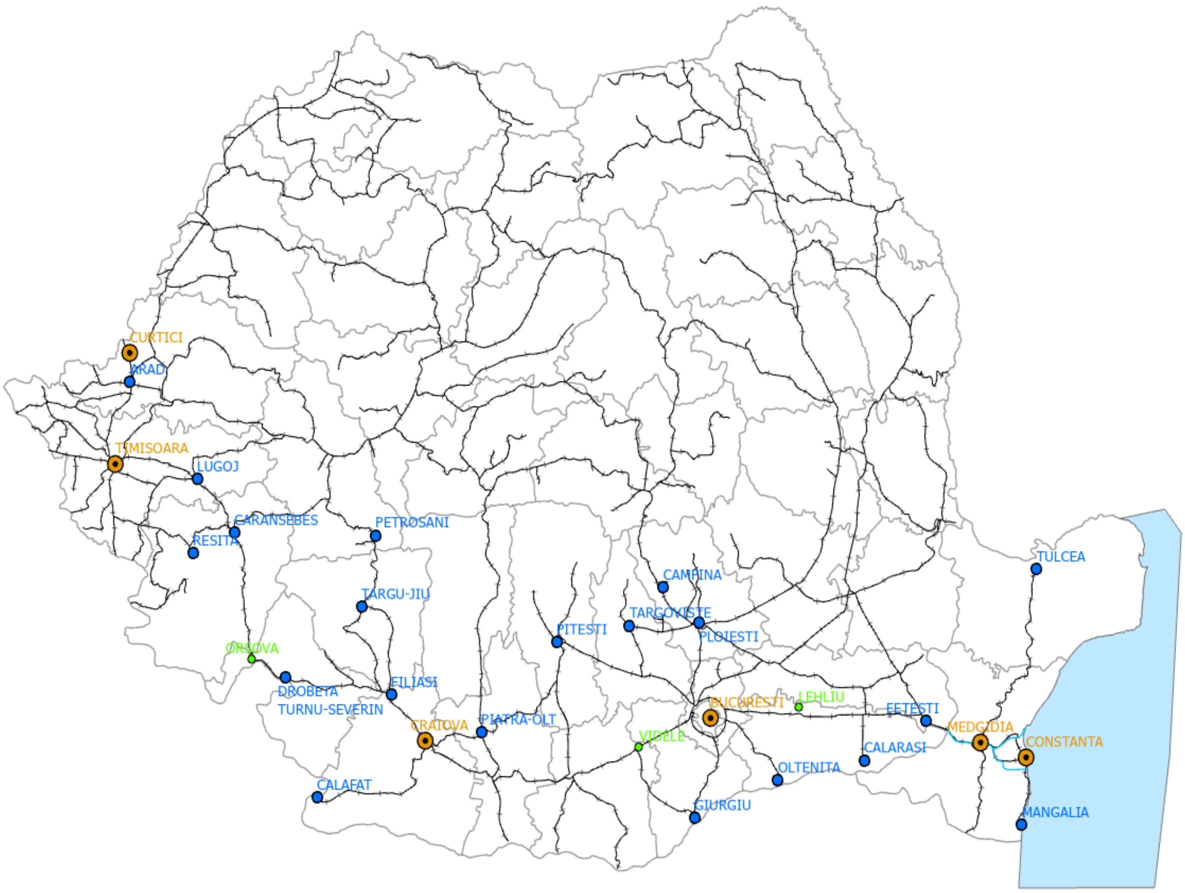


Figura 4.1. Railway network analyzed in order to obtain the optimal solution for setting up railway traffic entities

Another hypothesis taken into account is that between the technical stations of the whole railway network considered there are sectioning points where loading or unloading of goods from wagons is carried out. The exchange of wagons between the considered regional railways (R_1 - Bucharest, R_2 - Constanța, R_3 - Craiova and R_4 - Timișoara) is further presented in tabelar form (Table 4.1).

Tabel 4.1. **The wagons exchange between the four major railway lines**

From \ To	R_1	R_2	R_3	R_4	Total
R_1	374	228	178	167	**947**
R_2	248	251	195	177	**871**
R_3	305	250	366	359	**1271**
R_4	416	338	402	480	**1636**
Total	**1343**	**1067**	**1141**	**1174**	**4725**

All wagons dispatched from a regional railway are reported to the nearest technical station (located in the area of influence of the regional railway) in the direction of travel of the train sets. Tables 4.2 and 4.3 are prepared for both rail directions. The sizes that characterize the percentage of the total wagon exchange between regionals are generally constant values for an origin-destination relationship. The values are determined on the basis of the wagon currents calculated according to the calculation method presented above.

Tabel 4.2. **Wagon flow exchange on the even direction of the major railway line**

No.	Relation	Shipping Regional Railway	Destination Regional Railway	Flow value	Flow value between regional railway	Percentage [%]
1	Constanța - Medgidia	R_2	R_2	66	251	26,29
2	Constanța – București	R_2	R_1	147	248	59,27
3	Constanța – Craiova	R_2	R_3	99	195	50,77
4	Constanța – Timișoara	R_2	R_4	58	177	32,77
5	Constanța – Curtici	R_2	R_4	54	177	30,51
6	Medgidia- București	R_2	R_1	61	248	24,60
7	Medgidia- Craiova	R_2	R_3	78	195	40,00
8	Medgidia- Timișoara	R_2	R_4	29	177	16,38
9	Medgidia- Curtici	R_2	R_4	30	177	16,95
10	București - Craiova	R_1	R_3	177	178	99,44
11	București – Timișoara	R_1	R_4	75	167	44,91
12	București - Curtici	R_1	R_4	74	167	44,31

No.	Relation	Shipping Regional Railway	Destination Regional Railway	Flow value	Flow value between regional railway	Percentage [%]
13	Craiova – Timişoara	R_3	R_3	83	366	22,68
		R_3	R_4	156	359	43,45
14	Craiova – Curtici	R_3	R_4	200	359	55,71
15	Timişoara - Curtici	R_4	R_4	132	480	27,50

Tabel 4.3. **Wagon flow exchange on the odd direction of the major railway line**

No.	Relation	Shipping Regional Railway	Destination Regional Railway	Flow value	Flow value between regional railway	Percentage [%]
1	Curtici – Timşoara	R_4	R_4	28	480	5,83
2	Curtici – Craiova	R_4	R_4	11	480	2,29
		R_4	R_3	48	402	11,94
3	Curtici – București	R_4	R_1	64	416	15,38
		R_3	R_1	31	305	10,16
4	Curtici – Medgidia	R_4	R_2	16	338	4,73
5	Curtici – Constanța	R_4	R_2	38	338	11,24
6	Timişoara – Craiova	R_4	R_4	126	480	26,25
		R_4	R_3	172	402	42,79
7	Timişoara – București	R_4	R_1	238	416	57,21
		R_4	R_3	72	402	17,91
8	Timişoara – Medgidia	R_4	R_2	65	338	19,23
9	Timişoara – Constanța	R_4	R_2	175	338	51,78
10	Craiova - București	R_3	R_3	145	366	39,62
		R_3	R_1	199	305	65,25
11	Craiova - Medgidia	R_3	R_2	62	250	24,80
12	Craiova – Constanța	R_3	R_2	152	250	60,80
13	București – Medgidia	R_3	R_2	11	250	4,40
		R_1	R_2	77	228	33,77
14	București – Constanța	R_3	R_2	25	250	10,00
		R_1	R_2	145	228	63,60
15	Medgidia - Constanța	R_2	R_2	61	251	24,30

Tabel 4.4. **Wagon flows exchange between the six main technical stations of the railway line**

La / De la	Constanța (1)	Medgidia (2)	București (3)	Craiova (4)	Timișoara (5)	Curtici (6)
Constanța (1)	-	66	147	99	58	54
Medgidia (2)	61	-	61	78	29	30
București (3)	170	88	-	177	75	74
Craiova (4)	152	62	344	-	239	200
Timișoara (5)	65	175	310	298	-	132
Curtici (6)	38	16	95	59	28	-

By applying the relationship of the consumption of wagons - hours accumulation of a wagon set, we obtain:

$$\Omega_{ac,1} = 0,5\cdot 22\cdot\left(1-\frac{1}{5\cdot 1,2}\right)\cdot 60 = 550 \text{ wagons-hours accumulation}$$

$$\Omega_{ac,2} = 0,5\cdot 20\cdot\left(1-\frac{1}{5\cdot 1,2}\right)\cdot 60 = 500 \text{ wagons-hours accumulation}$$

$$\Omega_{ac,3} = 0,5\cdot 24\cdot\left(1-\frac{1}{5\cdot 1,2}\right)\cdot 60 = 600 \text{ wagons-hours accumulation}$$

$$\Omega_{ac,4} = 0,5\cdot 21\cdot\left(1-\frac{1}{5\cdot 1,2}\right)\cdot 60 = 525 \text{ wagons-hours accumulation}$$

$$\Omega_{ac,5} = \Omega_{ac,6} = 0,5\cdot 20\cdot\left(1-\frac{1}{4\cdot 1,2}\right)\cdot 60 = 500 \text{ wagons-hours accumulation}$$

We will also determine the time savings resulting from the transit of the current of wagons without processing in the technical stations (t_{ec}^{k}):

- for station (2) : t_{prel}^{II} = 12,3 [hours], t_{acum}^{II} = 11 [hours], t_{tranz}^{II} = 0,3 [hours] and r_1^{II} = 2 => time savings will be t_{ec}^{II} = 12,3 – 11 – 0.3 + 2 = 3 [hours]
- for station (3) : t_{prel}^{III} = 13 [ore], t_{acum}^{III} = 11,7 [hours], t_{tranz}^{III} = 0,3 [hours] and r_2^{III} = 3 => time savings will be t_{ec}^{III} = 13 – 11,7 – 0.3 + 3 = 4 [hours]
- for station (4) : t_{prel}^{IV} =11,4 [hours], t_{acum}^{IV} =10 [hours], t_{tranz}^{IV} = 0,4 [ore] and r_3^{IV} = 2 => time savings will be t_{ec}^{IV} = 11,4 – 10 – 0.4 + 2 = 3 [hours]
- for station (5) : t_{prel}^{V} = 12,5 [ore], t_{acum}^{V} = 10 [hours], t_{tranz}^{V} = 1 [hours] and r_1^{V} = 2 => time savings will be t_{ec}^{V} = 12,5 – 10 – 1 + 2 = 3,5 [hours]

Starting from the step diagrams of the wagon currents for both flow lines of the analysis railway line (figure 4.2), we will move on to the next step, namely the application of algorithms based on conjugate analytical comparison methods, direct calculation method and absolute calculation method.

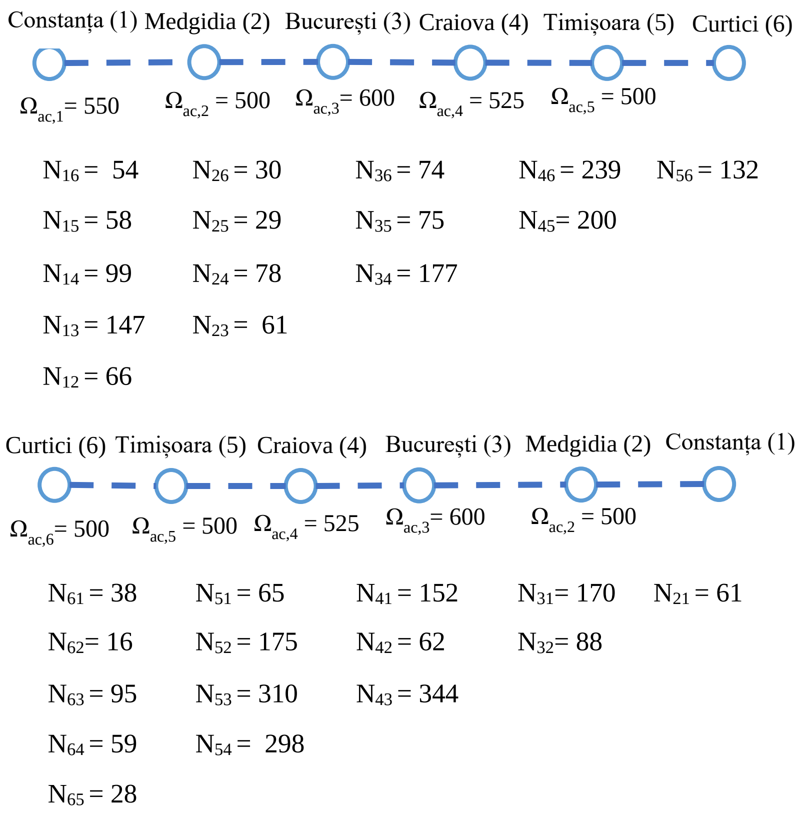
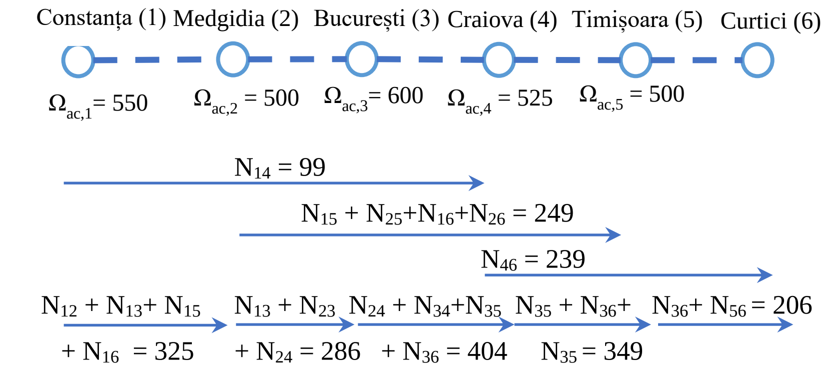


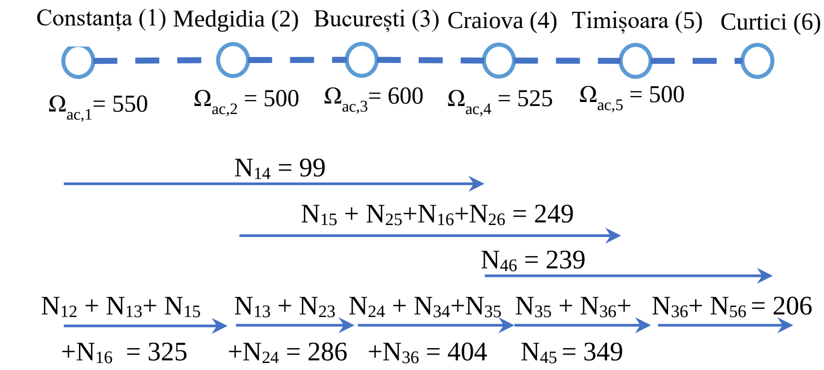
Figure 4.2. **Wagons flows diagram on the analysis railway line on the even and the odd traffic direction**

Optimal solution of railway traffic entities consolidation	**Wagons - hours consumption of the solution**



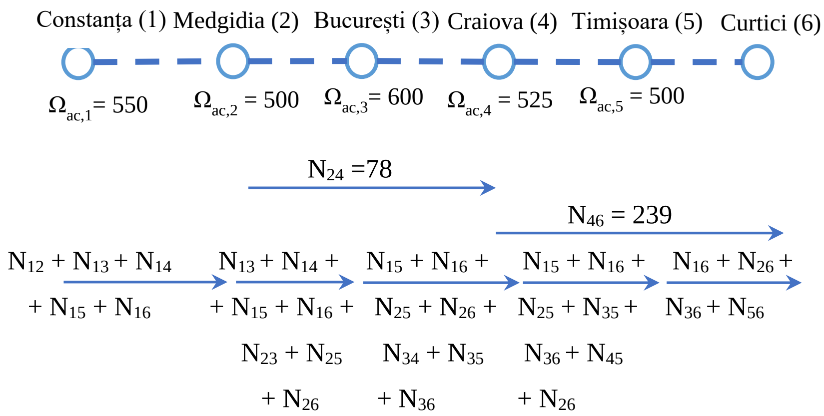
By using conjugated comparisons analysis method:

- Number of processed wagons : 725
- Wagons-hours accumulation : 2125
- Wagons-hours processing: 2308
- Total wagons-hours accumulation and processing : 4433 wagons-hours



By using the heuristic method :

- Number of processed wagons: 725
- Wagons-hours accumulation: 2125
- Wagons-hours processing: 2308
- Total wagons-hours accumulation and processed: 4433 wagons-hours

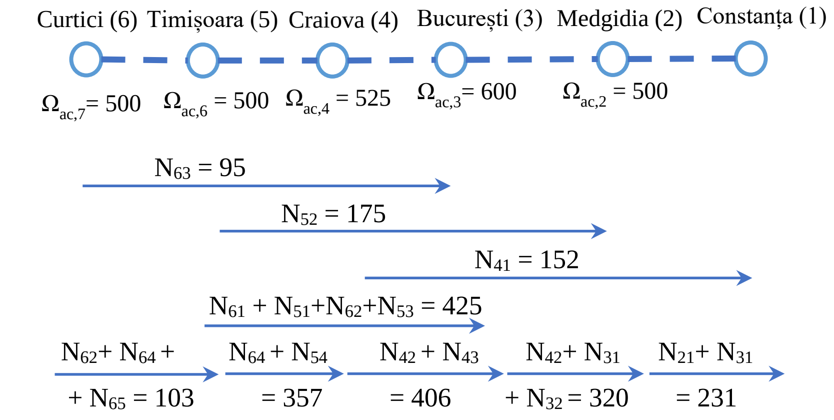


By appying absolute calculation method :

- Total wagons-hours consumption for accumulation and processing : $\Omega_2 + \Omega_4 + (N_{2,5} + N_{2,6})\, t_{ec}^{4} + (N_{3,5} + N_{3,6})\, t_{ec}^{4} + (N_{1,3} + N_{1,4} + N_{1,5} + N_{1,6})\, t_{ec}^{5}$ = 2902 wagons-hours

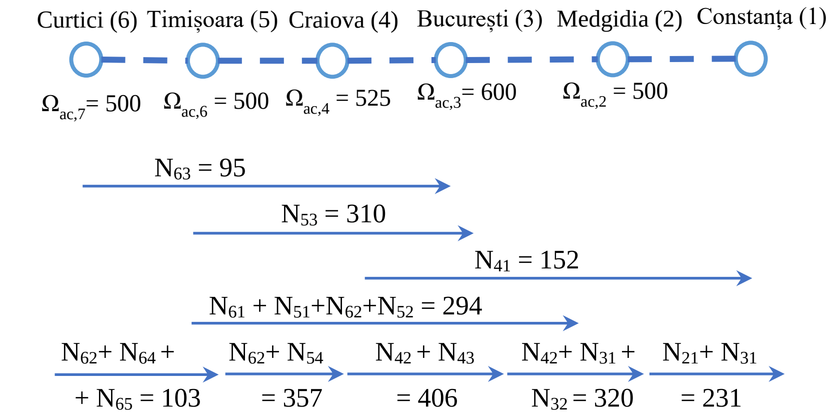
Figure 4.3. **The optimal variant of the monogroup railway entities formation for the even direction of the major railway line**

Optimal solution of railway traffic entities consolidation	Wagons - hours consumption of the solution



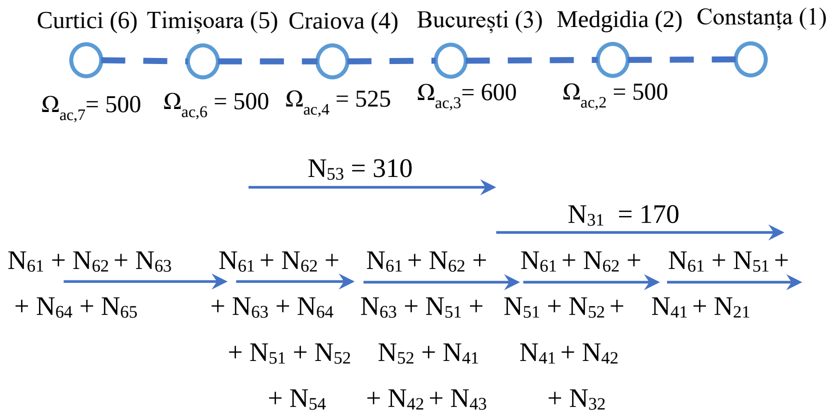
By using conjugated comparisons analysis method :

- Number of processed wagons: 736
- Wagons-hours accumulation: 2125
- Wagons-hours processing: 2273
- Total wagons-hours accumulation and processing: 4398 wagons-hours



By using the heuristic method:

- Number of processed wagons: 580
- Wagons-hours accumulation: 2125
- Wagons-hours processing: 1829
- Total wagons-hours accumulation and processing: 3954 wagons-hours



By appying absolute calculation method:

- Total wagons-hours consumption for accumulation and processing: $\Omega_5 + \Omega_3 + (N_{5,1} + N_{5,2})\, t_{ec}^3 + (N_{4,1} + N_{4,3})\, t_{ec}^3 + (N_{6,4} + N_{6,3} + N_{6,2} + N_{6,1})\, t_{ec}^5$ = 4797 wagons-hours

Figure 4.4. **The optimal variant of the monogroup railway entities formation for the odd direction of the major railway line**

4.2. Flows for urban distribution (specific for collaborative logistics)

Freight transport in large urban areas is one of the major challenges due to its importance in the economic functioning of the town as well as its impact on the quality of life of its inhabitants. Commodity flows related to urban logistics (depending on size, frequency and structure) are considered to be part of large distribution (Crainic et al., 2013). Therefore, it is necessary to identify a methodology that allows the choice of advantageous solutions to streamline the process of consolidating the flows of goods needed for urban distribution. In order to obtain a feasible and durable logistics solution, a collaborative logistics scheme containing a number of four distribution centers will be chosen and illustrated in Figure 4.5. The working hypotheses of the case study are the following (Raicu et al., 2020):

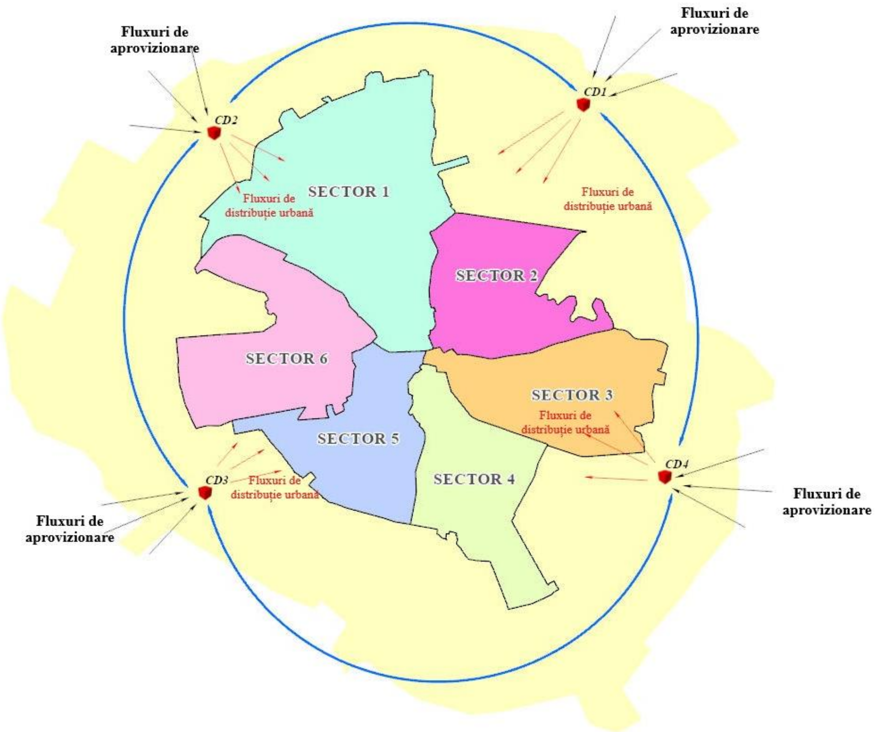
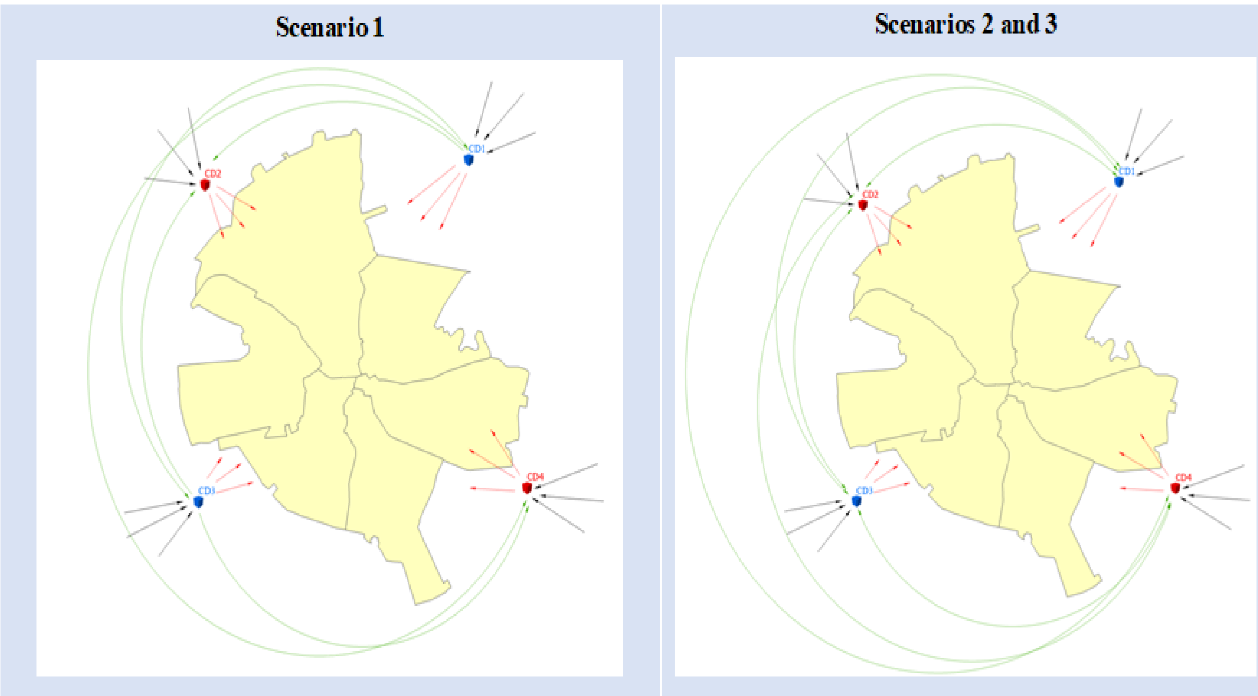


Figure 4.5. Amplasarea celor patru centre de distribuție urbană în schema de colaborare pe orizontală considerată

- each supplier supplies only one urban distribution center (which is the least affected by traffic congestion);
- all four urban distribution centers considered are located in such a way as to ensure easy transfer of goods between them;

- the producers do not have the necessary association capacities to be able to carry out the consolidation platform;
- deliveries (in this case, they are represented by palletized goods) that arrive in one of the considered urban distribution centers are subsequently transmitted to the other centers;
- reciprocal exchanges of goods of different categories can be made between each urban distribution center so that it can respond to the requests of traders for certain assortments of products;
- each of the four urban distribution centers has a warehouse designed to serve all customers and a logistics platform in which the goods are received, consolidated and shipped to the other distribution centers.

The following three urban distribution scenarios will be analyzed (these are exemplified in Figure 4.6):



Legend

Supply flow

Urban traffic flow (distribution flow)

Traffic flow between urban distribution centers in the collaborative scheme

Distribution centers with storage capacities and the possibility of collaborative exchanges

Distribution centers with only storage capacity

Figure 4.6. Freight flow consolidation schemes corresponding to the three scenarios considered

- **<u>Scenaro 1</u>** : Of the four urban distribution centers considered, only three have accessibility according to the requirements of the suppliers.
- **<u>Scenario 2</u>** : Similar to scenario one, the main difference being that the segment of the road network on which the urban distribution centers are located has been closed with effects in the sense of reducing the distances between some urban distribution centers.
- **<u>Scenario 3</u>** : Similar to scenario 2 except that in this case the possibility of consolidating the grouped urban traffic flows is analyzed.

It will be considered that only one type of vehicle is used in the distribution between the logistics platforms and that has a loading capacity m = 20 pallets, the size of the parameter that characterizes pallets accumulation in urban distribution centers c = $0,5 \cdot 24 \cdot \left(1 - \frac{1}{5 \cdot 1,2}\right)$ = 10 [hours].

In order to identify the optimal solution for consolidating urban traffic flows, the possible consolidation variants will be analyzed by applying the methods of absolute calculation and conjugate analytical comparisons, respectively the algorithm for consolidating grouped traffic flows. Whether **Scenario 1** is considered, it is assumed that only two of the four urban distribution centers have accessibility according to the requirements of the suppliers. The flows between the two distribution centers that have a logistics platform and the rest of the centers that do not have such a facility are represented in Figure 4.7.

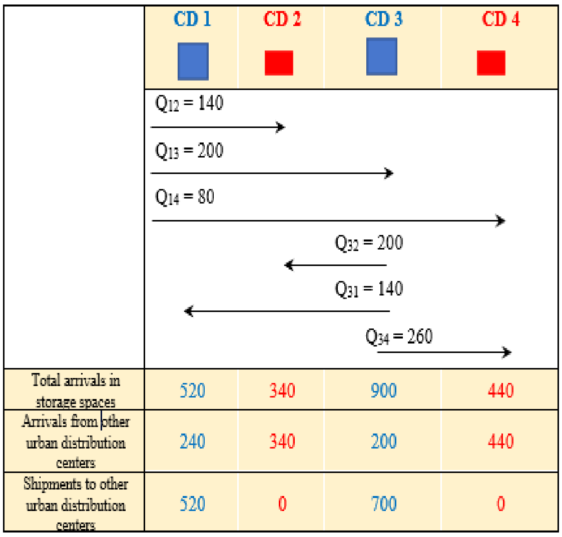
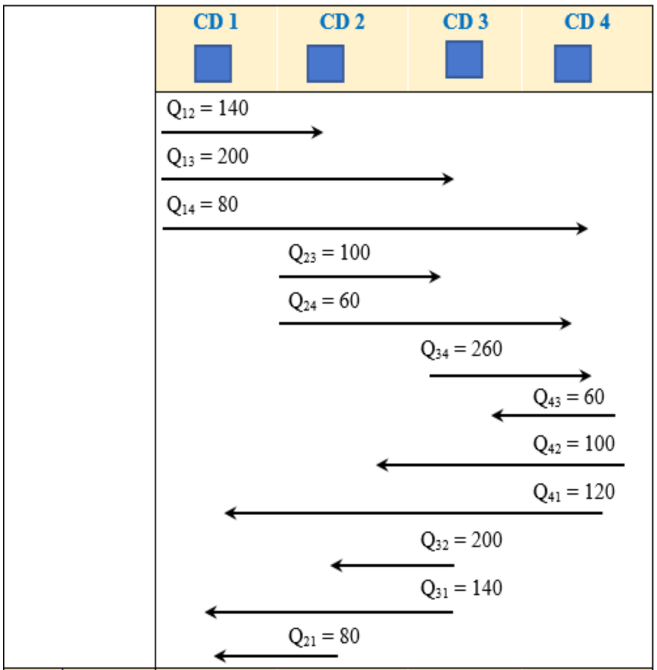


Figure 4.7. The flow of palletized goods from suppliers to the three urban distribution centers that have logistics platforms according to scenario 1

Scenario 2 assumes that all four urban distribution centers considered can be used by suppliers, thus generating the flow of palletized goods in figure 4.8. In this situation, all nine possible flow consolidation options given by the absolute calculation method must be analyzed and the one that guarantees the minimum as well as the optimal variant given by the combined analytical comparison and direct analytical methods must be identified.

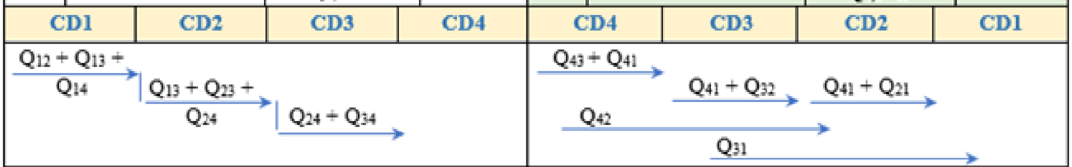


	CD 1	CD 2	CD 3	CD 4
Total arrivals in storage areas	540	640	560	600
Arrivals from other urban distribution centers	340	440	360	400
Shipments to other urban distribution centers	420	240	660	280

Figure 4.8. Flow of palletized goods from suppliers to the six urban distribution centers that are considered in scenario 2

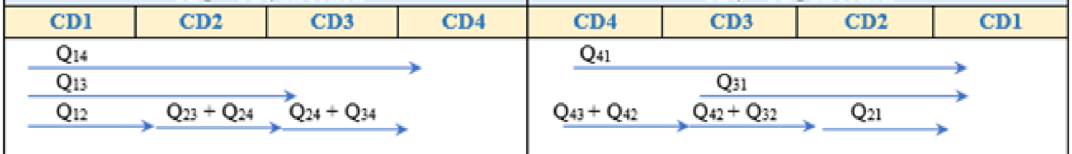
Applying the methods of conjugate analytical comparisons and direct analytical calculation to consolidate traffic flows, the solutions identified for the two directions of traffic through are illustrated in Figure 4.9.

ABSOLUTE CALCULATION METHOD OF TRAFFIC FLOWS CONSOLIDATION							
$CD_1 - CD_4$ direction				$CD_4 - CD_1$ direction			
No.	**Flow guidance**	**Pallet consumption - accumulation and processing hours**	**Value [palltes – hours]**	**No.**	**Flow guidance**	**Pallet consumption - accumulation and processing hours**	**Value [palltes – hours]**
1	Q_{13}, Q_{14}, Q_{24}	$2\Omega_1 + \Omega_2$	600	1	Q_{42}, Q_{41}, Q_{31}	$2\Omega_4 + \Omega_3$	600
2	$Q_{12} + Q_{13}, Q_{14}, Q_{24}$	$\Omega_1 + \Omega_2 + Q_{1,3}\, t_{ec}^2$	700	2	$Q_{43} + Q_{42}, Q_{41}, Q_{31}$	$\Omega_4 + \Omega_3 + Q_{4,2}\, t_{ec}^3$	600
3	$Q_{13} + Q_{14}, Q_{24}$	$\Omega_1 + \Omega_2 + Q_{1,4}\, t_{ec}^2$	520	3	$Q_{42} + Q_{41}, Q_{31}$	$\Omega_4 + \Omega_3 + Q_{4,1}\, t_{ec}^3$	640
4	$Q_{12} + Q_{13} + Q_{14}, Q_{24}$	$\Omega_2 + (Q_{1,3} + Q_{1,4})\, t_{ec}^2$	620	4	$Q_{41} + Q_{42} + Q_{43}, Q_{31}$	$\Omega_3 + (Q_{4,2} + Q_{4,1})\, t_{ec}^3$	640
5	$Q_{13}, Q_{14}, Q_{23} + Q_{24}$	$2\Omega_1 + Q_{2,4}\, t_{ec}^3$	520	5	$Q_{42}, Q_{41}, Q_{32} + Q_{31}$	$2\Omega_4 + Q_{3,1}\, t_{ec}^2$	610
6	$Q_{12} + Q_{13}, Q_{14}, Q_{23} + Q_{24}$	$\Omega_1 + Q_{1,3}\, t_{ec}^2 + Q_{2,4}\, t_{ec}^3$	640	6	$Q_{12} + Q_{13}, Q_{14}, Q_{32} + Q_{31}$	$\Omega_4 + Q_{4,2}\, t_{ec}^3 + Q_{3,1}\, t_{ec}^2$	610
7	**$Q_{13} + Q_{14}, Q_{23} + Q_{24}$**	**$\Omega_1 + Q_{1,4}\, t_{ec}^3 + Q_{2,4}\, t_{ec}^3$**	**480**	7	$Q_{42} + Q_{41}, Q_{32} + Q_{31}$	$\Omega_4 + Q_{4,1}\, t_{ec}^2 + Q_{3,1}\, t_{ec}^2$	590
8	$Q_{12} + Q_{13} + Q_{14}, Q_{23} + Q_{24}$	$(Q_{1,3} + Q_{1,4})\, t_{ec}^2 + (Q_{1,4} + Q_{2,4})\, t_{ec}^3$	700	8	$Q_{41} + Q_{42} + Q_{43}, Q_{32} + Q_{31}$	$(Q_{4,2} + Q_{4,1})\, t_{ec}^3 + (Q_{4,1} + Q_{4,2})\, t_{ec}^2$	770
9	$Q_{12} + Q_{14}, Q_{13}, Q_{24}$	$\Omega_1 + \Omega_2 + Q_{1,4}\, t_{ec}^3$	560	**9**	**$Q_{43} + Q_{41}, Q_{42}, Q_{31}$**	**$\Omega_4 + \Omega_3 + Q_{4,1}\, t_{ec}^2$**	**580**



CONJUGATED ANALYTICAL COMPARISONS METHOD FOR TRAFFIC FLOWS CONSOLIDATION

$CD_1 - CD_4$ direction	$CD_4 - CD_1$ direction



DIRECT ANALYTICAL CALCULATION METHOD FOR TRAFFIC FLOWS CONSOLIDATION

$CD_1 - CD_4$ direction	$CD_4 - CD_1$ direction

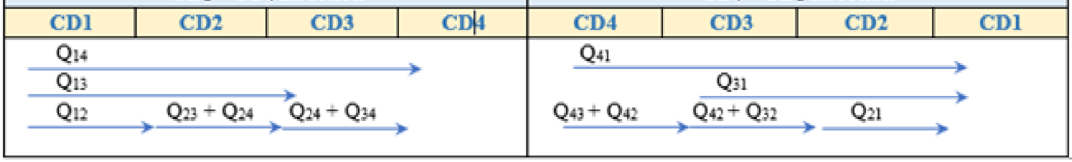
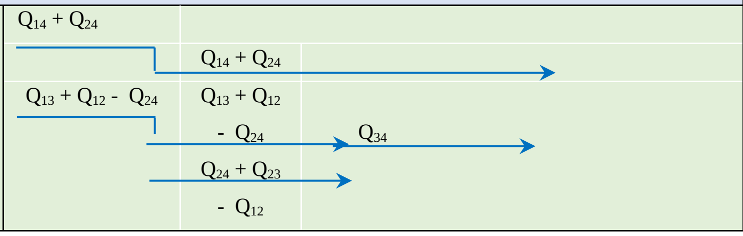
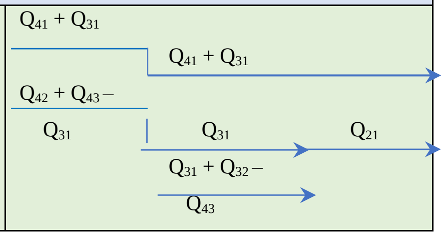


Figure 4.9. Optimal solutions for consolidating urban traffic flows for both directions

Scenario 3 will analyze the possibility of setting up grouped traffic entities in the whole horizontal collaboration scheme considered, which involves analyzing a number of 22 possible options for setting up urban traffic entities from the perspective of pallet consumption - hours of accumulation and processing. The analysis of the possible variants of consolidation of the grouped urban traffic flows was performed in table 4.5 for the two directions.

Tabel 4.5. Traffic flow consolidation algorithm for multiple destinations for directions CD1 – CD4, CD4 – CD1 respectively

Var.no.	Scheme of consolidation variant for CD1 – CD4 direction	Condition to apply the consolidation scheme	Scheme of consolidation variant for CD4 – CD1 direction	Condition to apply the consolidation scheme	Value of pallets – hours consumption for CD1 – CD4 direction	Value of pallets – hours consumption for CD4 – CD1 direction
1	$Q_{14}, Q_{13}, Q_{12}, Q_{24} + Q_{23}, Q_{24} + Q_{34}$	$Q_{24} = Q_{23}$	$Q_{43}, Q_{42}, Q_{43}, Q_{31} + Q_{32}, Q_{31} + Q_{21}$	$Q_{31} = Q_{32}$	1100,625	1199,037
2	$Q_{14}, Q_{13} + Q_{12}, Q_{24} + Q_{23}, Q_{13} + Q_{23} - Q_{34}, Q_{24} + Q_{34}$	$Q_{14} + Q_{13} + Q_{23} + Q_{24} < Q_{14} + Q_{24} + Q_{34}$	$Q_{41}, Q_{42} + Q_{43}, Q_{31} + Q_{32}, Q_{42} + Q_{32} – Q_{21}, Q_{32} + Q_{21}$	$Q_{41} + Q_{42} + Q_{32} + Q_{31} < Q_{41} + Q_{31} + Q_{21}$	1721,05	1449,090
3	$Q_{14} + Q_{13} + Q_{12}, Q_{14} + Q_{24} + Q_{34}, Q_{13} + Q_{24} - Q_{34}$	$Q_{14} + Q_{13} + Q_{23} + Q_{24} > Q_{14} + Q_{24} + Q_{34}$	$Q_{14} + Q_{13} + Q_{12}, Q_{14} + Q_{24} + Q_{34}, Q_{13} + Q_{24} - Q_{34}$	$Q_{41} + Q_{42} + Q_{32} + Q_{31} > Q_{41} + Q_{31} + Q_{21}$	1609,692	1717,560
4	$Q_{14} + Q_{13}, Q_{12}, Q_{24} + Q_{34} – Q_{13}, Q_{13} + Q_{24} - Q_{34}$	$Q_{14} + Q_{13} + Q_{23} + Q_{24} > Q_{14} + Q_{24} + Q_{34}$ și $Q_{34} > Q_{13}$	$Q_{41} + Q_{42}, Q_{43}, Q_{31} + Q_{32} – Q_{42}, Q_{43} + Q_{31} – Q_{21}$	$Q_{41} + Q_{42} + Q_{32} + Q_{31} > Q_{41} + Q_{31} + Q_{21}$ și $Q_{21} > Q_{42}$	1045,35	1225,098
5	$Q_{14} + Q_{13}, Q_{12}, Q_{24} + Q_{23}, Q_{14} + Q_{24} + Q_{34}, Q_{24} – Q_{14} – Q_{13}$	$Q_{23} > Q_{14} + Q_{34}$	$Q_{41} + Q_{42}, Q_{43}, Q_{31} + Q_{32}, Q_{41} + Q_{31} + Q_{21}, Q_{21} – Q_{41} – Q_{42}$	$Q_{31} > Q_{41} + Q_{21}$	1104,926	1249,411
6	$Q_{14} + Q_{13} + Q_{12}, Q_{14} + Q_{24} + Q_{34}, Q_{24} – Q_{12} + Q_{23}$	$Q_{14} + Q_{13} + Q_{12} < Q_{14} + Q_{13} + Q_{23} + Q_{24}$	$Q_{43} + Q_{42} + Q_{43}, Q_{41} + Q_{31} + Q_{21}, Q_{31} – Q_{43} + Q_{32}$	$Q_{41} + Q_{42} + Q_{43} < Q_{41} + Q_{42} + Q_{32} + Q_{31}$	1285,416	1247,184
7	$Q_{14}, Q_{13} + Q_{12}, Q_{24} + Q_{34}, Q_{24} + Q_{23} – Q_{12}$	$Q_{14} + Q_{13} + Q_{12} < Q_{14} + Q_{13} + Q_{23} + Q_{24}$	$Q_{41}, Q_{42} + Q_{43}, Q_{31} + Q_{21}, Q_{31} + Q_{32} – Q_{43}$	$Q_{41} + Q_{42} + Q_{43} < Q_{41} + Q_{42} + Q_{32} + Q_{31}$	1258,45	1152,573
8	$Q_{14} + Q_{24}, Q_{13} + Q_{12} - Q_{24}, Q_{24}, Q_{24} + Q_{23} – Q_{12}, Q_{34}$	$Q_{14} + Q_{13} + Q_{12} < Q_{14} + Q_{24} + Q_{34}$ și $Q_{12} > Q_{24}$	$Q_{41} + Q_{31}, Q_{42} + Q_{43} - Q_{31}, Q_{31}, Q_{31} + Q_{32} – Q_{43}, Q_{21}$	$Q_{41} + Q_{42} + Q_{43} < Q_{41} + Q_{31} + Q_{21}$ și $Q_{42} > Q_{31}$	**1007,783**	**1100,514**
9	$Q_{12} + Q_{13} + Q_{14}, Q_{12} – Q_{23}, Q_{14} + Q_{34}, Q_{24}$	$Q_{12} > Q_{23}$	$Q_{41} + Q_{42} + Q_{43}, Q_{43} – Q_{32}, Q_{41} + Q_{21}, Q_{31}$	$Q_{41} > Q_{32}$	1340	1242,214
10	$Q_{14}, Q_{13} + Q_{12}, Q_{24}, Q_{23} – Q_{12}, Q_{34}$	$Q_{12} < Q_{23}$	$Q_{41}, Q_{42} + Q_{43}, Q_{31}, Q_{32} – Q_{43}, Q_{21}$	$Q_{43} < Q_{32}$	1313,333	1152,5
11	$Q_{14} + Q_{13}, Q_{12}, Q_{24}, Q_{23}, Q_{24} – Q_{13}$	$Q_{13} < Q_{34}$	$Q_{41} + Q_{42}, Q_{43}, Q_{31}, Q_{32}, Q_{31} – Q_{42}$	$Q_{13} < Q_{34}$	1284,395	1136,8
12	$Q_{14} + Q_{24}, Q_{13} + Q_{12} - Q_{24}, Q_{13} + Q_{23}, Q_{23} – Q_{13} – Q_{12}, Q_{34}$	$Q_{24} < Q_{13} + Q_{12}$	$Q_{41} + Q_{31}, Q_{42} + Q_{43} - Q_{31}, Q_{42} + Q_{32}, Q_{32} – Q_{42} – Q_{43}, Q_{21}$	$Q_{31} < Q_{42} + Q_{43}$	1391,428	1292,307
13	$Q_{12} + Q_{13} + Q_{14}, Q_{23} – Q_{13} – Q_{12}, Q_{13} + Q_{23}, Q_{34}$	$Q_{24} > Q_{13} + Q_{12}$	$Q_{41} + Q_{42} + Q_{43}, Q_{32} – Q_{42} – Q_{43}, Q_{42} + Q_{32}, Q_{21}$	$Q_{31} > Q_{42} + Q_{43}$	1567 *	1259,254 *
14	$Q_{14} + Q_{13}, Q_{12}, Q_{24} + Q_{23}, Q_{24} + Q_{34} – Q_{13}$	$Q_{14} + Q_{24} + Q_{34} > Q_{14} + Q_{13}$	$Q_{42} + Q_{43}, Q_{31} + Q_{32}, Q_{31} + Q_{21} – Q_{42}$	$Q_{41} + Q_{31} + Q_{21} > Q_{41} + Q_{42}$	1948,21 *	1219,256 *
15	$Q_{12} + Q_{13} + Q_{14}, Q_{24} + Q_{34} – Q_{12} – Q_{13}, Q_{13} + Q_{23} – Q_{34}$	$Q_{14} + Q_{13} + Q_{23} + Q_{24} = Q_{14} + Q_{24} + Q_{34} > Q_{14} + Q_{13} + Q_{12} + Q_{34}$	$Q_{41} + Q_{42} + Q_{43}, Q_{31} + Q_{21} – Q_{43} – Q_{42}, Q_{42} + Q_{32} – Q_{21}$	$Q_{41} + Q_{42} + Q_{32} + Q_{31} = Q_{41} + Q_{31} + Q_{21} > Q_{41} + Q_{42} + Q_{43} + Q_{21}$	We obtain a negative value, therefore the variant will be exclued from next calculations	We obtain a negative value, therefore the variant will be exclued from next calculations
16	$Q_{12} + Q_{13} + Q_{14}, Q_{24}, Q_{23} – Q_{12}, Q_{34} – Q_{23} – Q_{12}$	$Q_{13} + Q_{14} + Q_{23} + Q_{24} > Q_{14} + Q_{24} + Q_{34} = Q_{14} + Q_{13} + Q_{12} + Q_{24}$	$Q_{41} + Q_{42} + Q_{43}, Q_{31}, Q_{32} – Q_{43}, Q_{21} – Q_{32} – Q_{41}$	$Q_{41} + Q_{42} + Q_{32} + Q_{31} > Q_{41} + Q_{31} + Q_{21} = Q_{41} + Q_{42} + Q_{43} + Q_{31}$	714,852 *	1150,785 *
17	$Q_{14}, Q_{13} + Q_{12}, Q_{24} – Q_{23} – Q_{12}, Q_{34} – Q_{23} – Q_{12}$	$Q_{14} + Q_{13} + Q_{12} < Q_{14} + Q_{13} + Q_{23} + Q_{24}$	$Q_{41}, Q_{42} + Q_{43}, Q_{31} – Q_{32} – Q_{43}, Q_{21} – Q_{32} – Q_{43}$	$Q_{41} + Q_{42} + Q_{43} < Q_{41} + Q_{42} + Q_{32} + Q_{31}$	1288, 748 *	2642, 187 *
18	$Q_{12} + Q_{13} + Q_{14}, Q_{24} – Q_{23} – Q_{12}, Q_{34} – Q_{23} – Q_{13}$	$Q_{14} + Q_{13} + Q_{12} < Q_{14} + Q_{13} + Q_{23} + Q_{24} < Q_{14} + Q_{24} + Q_{34}$	$Q_{41}, Q_{42} + Q_{43}, Q_{31} – Q_{32} – Q_{43}, Q_{21} – Q_{32} – Q_{43}$	$Q_{41} + Q_{42} + Q_{43} < Q_{41} + Q_{42} + Q_{32} + Q_{31} < Q_{41} + Q_{31} + Q_{21}$	1304, 892 *	1538, 881 *
19	$Q_{14}, Q_{13} + Q_{12}, Q_{24} + Q_{34} – Q_{12} – Q_{13}, Q_{24} + Q_{34} – Q_{12} – Q_{13}$	$Q_{14} + Q_{13} + Q_{12} < Q_{14} + Q_{13} + Q_{23} + Q_{24} < Q_{14} + Q_{24} + Q_{34}$	$Q_{41}, Q_{42} + Q_{43}, Q_{31} + Q_{21} – Q_{43} – Q_{43}, Q_{31} + Q_{21} – Q_{43} – Q_{42}$	$Q_{41} + Q_{42} + Q_{43} < Q_{41} + Q_{42} + Q_{32} + Q_{31} < Q_{41} + Q_{31} + Q_{21}$	1431,148 *	1300,627 *
20	$Q_{14} + Q_{24} + Q_{34}, Q_{12} + Q_{13} – Q_{24} – Q_{34}, Q_{24} + Q_{23} – Q_{12}$	$Q_{14} + Q_{24} + Q_{34} < Q_{14} + Q_{13} + Q_{12} < Q_{14} + Q_{13} + Q_{23} + Q_{24}$ și $Q_{13} > Q_{34}$ și $Q_{12} > Q_{24}$	$Q_{41} + Q_{42} + Q_{43}, Q_{43} + Q_{42} – Q_{31} – Q_{21}, Q_{31} + Q_{323} – Q_{43}$	$Q_{41} + Q_{31} + Q_{21} < Q_{41} + Q_{42} + Q_{43} < Q_{41} + Q_{42} + Q_{32} + Q_{31}$ și $Q_{42} > Q_{21}$ și $Q_{43} > Q_{31}$	1669,272	1568,021 *
21	$Q_{12} + Q_{13} + Q_{14}, Q_{24} + Q_{23} – Q_{13}, Q_{24} + Q_{34} – Q_{12} – Q_{13}$	$Q_{14} + Q_{13} + Q_{23} + Q_{24} > Q_{14} + Q_{24} + Q_{34} < Q_{14} + Q_{24} + Q_{34}$ și $Q_{24} > Q_{12}$	$Q_{43} + Q_{42} + Q_{41}, Q_{31} + Q_{32} – Q_{42}, Q_{31} + Q_{21} – Q_{43} – Q_{42}$	$Q_{41} + Q_{42} + Q_{32} + Q_{31} > Q_{41} + Q_{31} + Q_{21} < Q_{41} + Q_{31} + Q_{21}$ și $Q_{31} > Q_{43}$	1194,410	1179,859
22	$Q_{12} + Q_{13} + Q_{14}, Q_{24} + Q_{23} – Q_{13}, Q_{24} + Q_{34} – Q_{12} – Q_{13}$	$Q_{14} + Q_{13} + Q_{23} + Q_{24} > Q_{14} + Q_{24} + Q_{34} < Q_{14} + Q_{24} + Q_{34}$	$Q_{43} + Q_{42} + Q_{41}, Q_{31} + Q_{32} – Q_{42}, Q_{31} + Q_{21} – Q_{43} – Q_{42}$	$Q_{41} + Q_{42} + Q_{32} + Q_{31} > Q_{41} + Q_{31} + Q_{21} < Q_{41} + Q_{31} + Q_{21}$	1371,250	1328,937

Var.no.	Scheme of consolidation variant for CD1 – CD4 direction	Condition to apply the consolidation scheme	Scheme of consolidation variant for CD4 – CD1 direction	Condition to apply the consolidation scheme	Value of pallets – hours consumption for CD1 – CD4 direction	Value of pallets – hours consumption for CD4 – CD1 direction
** The condition for applying the consolidation option is not met, therefore it cannot be applied and in some cases it is not possible to calculate the consumption of pallets - proper storage and processing hours*						
Consolidation scheme for CD1 – CD4 direction				**Consolidation scheme for CD4 – CD1 direction**		
Var. nr. 8				**Var. nr. 8**		

5. CONCLUSIONS

5.1. Final considerations

Following the elaboration of the doctoral thesis entitled "*Transport networks with flow consolidations*" the following conclusions are drawn:

- The problem of railway traffic entities formation is a complex one, being of a combinatorial nature in which multiple variants of the organization of wagon currents must be considered, as well as their possibilities of combination. In addition to analyzing these variants, a number of parameters - the size of the wagon currents, the duration of station wagons in the technical stations, the time required to accumulate the wagons, the accumulation parameter, the processing equivalent - significantly influence the choice of the optimal variant.
- The methods for the formation of railway traffic entities for a given destination are represented by the methods of absolute calculation, conjugate analytical comparisons and direct analytical calculation. It has been observed that the application of the algorithm for setting up railway traffic entities by the absolute calculation method has the disadvantage that, if the railway bus has more than seven basic technical stations and if possible mathematical variants are taken into account, the number of variants increases considerably. , most of which are also uneconomical.
- The algorithm of conjugate analytical comparisons method starts from the principle of gradually choosing the most advantageous relations and eliminating the inefficient

ones. The main advantage of the algorithm consists in the possibility of analyzing all the variants of setting up the railway traffic entities, not being influenced by the number and location of the train formation stations. Also, the algorithm allows the combination of railway traffic entities in all possible variants, starting both to the neighboring stations and to the others. In this way, both the optimal and the closest consolidation option can be established.

- The algorithm for establishing the optimal variant of railway traffic entities formation based on the heuristic method starts from their classification in basic currents that specialize unconditionally, basic currents, additional, complementary and unifiable. The algorithm has the advantage of quickly identifying the optimal solution in strict accordance with the processing possibilities of the technical or shunting yards of the railway network. The usefulness of this method is especially evident for those buses with a high number of technical stations, being thus characterized by an extra operability and simplicity of calculations.
- In order to make the railway transport activity more efficient, the possibility of identifying the ideal way to form traffic entities for several destinations must be analyzed because they ensure the reduction of wagon consumption - hours for accumulation, which also leads to reduced wagon turnover. The algorithm for setting up grouped railway traffic entities facilitates the determination of wagon consumption - hours for each variant of train consolidation for a single destination. The variants to be calculated are then chosen based on the existing link between the number of wagons corresponding to each destination but also the calculation of the wagon consumption - hours of the considered variants. Subsequently, the first three variants with the lowest consumption will be chosen and the possibilities of applying these solutions in practice will be checked. They will be checked in ascending order of consumption, the algorithm stopping when the verified version corresponds to the existing situation. It should be borne in mind that, in order to guide trains on the basis of a variant, it must be checked both in terms of the processing capacity of the station and in terms of the transit capacity of the track diagonals.

5.2. Personal contributions and future research directions

The author's contributions to the development of the field of studies Transport Engineering are underlined by various elements of both theoretical and practical nature that are presented in the doctoral thesis as results. Of these, the following can be mentioned:

- Carrying out a complex study of the literature and structuring the scientific works identified on thematic categories. Thus, scientific papers were studied in the field of general techniques for consolidating the demand for transport in the warehouses of transport networks (more precisely, the application of mathematical models for sizing and optimizing the activity in the warehouses) and how it influences this process, the entire performance of transport, mathematical models for consolidating freight flows by identifying the optimal location of terminals in the transmission network as well as mathematical models for consolidating rail traffic flows for a single or for multiple destinations.
- Development of mathematical models to streamline the consolidation of transport demand. Due to the uneven and increasing variations in transport demand, the problem of sizing all those constructions and installations subject to variable operating demands arises. In this sense, a probabilistic model of sizing the deposits within the consolidation terminals has been designed and applied, determining the optimal number of machines necessary to equip the handling fronts as well as the appropriate distribution of available resources for equipping the handling fronts and which must be consistent with all variations of transport demand.
- Development of mathematical models for the elaboration and identification of the optimal variant for the formation of railway traffic entities for a single destination or for multiple destinations. Mathematical models aim at choosing the optimal option for consolidating railway traffic entities (both for one destination and for multiple destinations) in terms of wagon consumption - hours for accumulation and processing.
- Adaptation and application of mathematical models for the establishment of railway traffic entities (both for a single destination and for multiple destinations) for the case of distribution of goods in large urban agglomerations.

With regard to future directions of research, a first category of problems is the difficulties in consolidating transport demand. Thus, new models need to be identified and developed to make the process of consolidating transport demand in warehouses more efficient using numerical simulation, developing new facilities for loading goods into means of transport as well as new mathematical models (taking into account several criteria) for staggering the investments needed to increase the performance of setting up transport entities.

Another category of problems discussed in the thesis is the ways of consolidating traffic flows. Future research directions should primarily focus on refining mathematical models for setting up traffic entities for a single destination (absolute calculation method, conjugate analytical comparisons and direct calculation) and for multiple destinations. Secondly, new methods to streamline the establishment of traffic entities of any kind should be developed by considering the different models of operational research (genetic algorithms, artificial intelligence, etc.). Also, all the categories of problems listed above should be extended and adapted in transport networks with enhanced passenger flows.

BIBLIOGRPHY (selection)

[1] Abramović, B., Zitricky, V., Biškup, V., *Organisation of railway freight transport: case study CIM/SMGS between Slovakia and Ukraine,* in European Transport Research Review, vol. 8(4), 2016, pag. 1 – 13

[2] Ackoff, R., Sansieni, W. , *Bazele cercetării operaționale*, Editura Tehnică, București, 1975

[3] Adan, I, Resing, J., *Queueing systems*, Department of Mathematics and Computing Science, Eindhoven, 2015

[4] Belošević, I., Jing, Y., Ivic, M., & Jovanovic, P., *Optimization Model for Multi-Stage Train Classification Problem at Tactical Planning Level,* 8th International Conference on Railway Operations Modelling and Analysis (ICROMA), Norrköping, Sweden, June 17th–20th 2019, No. 69, pag. 116-127, Linköping University Electronic Press

[5] Bodin, L. D., B. L. Golden, A. D. Schuster, W. Romig, *A model for the blocking of trains*, Transportation Res. B 14(1-2), pag. 115–120, 1980

[6] Bontekoning, Y., *Hub exchange operations in intermodal hub-and-spoke operations: comparison of the performances of four types of rail-rail exchange facilities*, Thesis (Ph.D.) -Technische Universiteit Delft, 2006

[7] Butko, T., Prokhorov, V., Chekhunov, D., *Devising a method for the automated calculation of train formation plan by employing genetic algorithms*, Eastern-European Journal of Enterprise Technologies, [S.l.], v. 1, n. 3 (85), pag. 55 – 61, 2017, ISSN 1729-4061

[8] Campbell, J.F, *Modeling economies of scale in transportation hub networks*, 46th Hawaii International Conference on System Sciences, pag. 1154 –1163, 2013

[9] Campbell, J., Ernst, A., Krishnamoorthy, M., *Hub Arc Location Problems: Part I—Introduction and results*, Vol. 51, No. 10, pag. 1540 –1555, 2005

[10] Campbell, J., Ernst, A., Krishnamoorthy, M., *Hub Arc Location Problems: Part II—Formulations and Optimal Algorithms*, Vol. 51, No. 10, pag. 1556 –1571, 2005

[11] Cordeau, J., Toth, P., Vigo, D., *A Survey of Optimization Models for Train Routing and Scheduling*, Volume 32, Issue 4, November 1998, pag. 306 – 404

[12] Costescu, D., *Cercetări privind reţeaua transporturilor multimodale la distanţe medii. Modele matematice şi de simulare pentru amplasarea şi dezvoltarea terminalelor*, Teză de doctorat, București, 2010

[13] Costescu, D., *Asupra modelării rețelelor de transport intermodal*, Buletinul AGIR, Supliment 1/2012, pag. 22 – 27

[14] *** *Council Regulation (EU) No 642/2014 of 16 June 2014* establishing the Shift2Rail Joint Undertaking, Official Journal of the European Union, vol. 57, June 2014, pag. 9 – 33

[15] Crainic, T.G., Ferland, J.A., Rousseau, J.M., *A tactical planning model for rail freight transportation*, in Transportation Science, vol. 18, no. 2, 1984, pag. 165 – 184

[16] Crainic, T.G., Marcotte, S., Rei, W., Takouda P.M., *Proactive Order Consolidation in Global Sourcing*. In: Bookbinder J. (eds) Handbook of Global Logistics. International Series in Operations Research & Management Science, vol 181. Springer, New York, NY, 2013

[17] Dancea, I., *Metode de optimizare*, Editura Dacia, Cluj – Napoca, 1976

[18] Engström, R., *The Roads Role in the freight transport systems*, Transportation Research Procedia, Volume 14, 2016, pag.1443 – 1452

[19] Farahani, RZ, Hekmaftar, M., Arabani, AB, *Hub location problems: a review of models, classification, solution techniques, and application*. Computers & Industrial Engineering, Volume 64, Issue 4, pag.1096-1109, 2013

[20] Frîncu, P., Tănăsuică, I., Raicu, Ș., *Folosirea mașinilor electronice cifrice în transportul feroviar*, Editura Transporturilor și Telecomunicațiilor, 1965

[21] Ghiani, G., Laporte, G., & Musmanno, R., *Introduction to logistics systems planning and control*, John Wiley & Sons, 2004

[22] Gattuso, D., Malara, M., Cassone, G.C., *Planning and Simulation of Intermodal Freight Transport on International Networks. Hub and Spoke System in Euro-Mediterranean Area*. Sustainability 2020, 12, 776

[23] Gu, J., Goetschalckx, M., McGinnis, L. F., R*esearch on warehouse operation: A comprehensive review*, European Journal of Operational Research, Volume 177, Nr. 1, pag. 1 – 21, 2007

[24] Ivić, M., & Kosijer, M., *Conditions for simultaneous formation of multigroup freight trains*, Građevinar, vol.64, no.7, pag. 553 – 563, 2012

[25] Jara-Díaz, S. R., Cortés, C. E., & Morales, G. A., *Explaining changes and trends in the airline industry: Economies of density, multiproduct scale, and spatial scope*, Transportation Research Part E: Logistics and Transportation Review, 60, pag.13 – 26, 2013

[26] Kocinev, F.P., Maksimovici, M., Tihonov, K.K., Cernomordik, G.I. , *Organizarea circulației la căile ferate*, Ministerul Căilor Ferate. Centrul de Documentare și Publicații Tehnice, 1969

[27] Kondratjev, J. , *Logistics.Transportation and warehouse in supply chain*, PhD Thesis, March 2015

[28] Kreutzberger, E., Konings, R., *The challenge of appropriate hub terminal and hub-and-spoke network development for seaports and intermodal rail transport in Europe*, Research in Transportation Business and Management, 2016, 19, pag. 83 – 96

[29] Masek, J., Camaj, J., Nedeliakova, E., *Application on the Queuing Theory in the Warehouse Optimization*, World Academy of Science, Engineering and Technology International Journal of Industrial and Manufacturing Engineering, Volume 9, No.11, 2015

[30] Morganti, G., Crainic, T.G., Frejinger, E. and Ricciardi, N., *Block planning for intermodal rail: Methodology and case study*. Transportation Research Procedia, 47, pag.19 – 26, 2020

[31] O'Kelly, M.E., *A quadratic integer program for the location of interacting hub facilities*, European journal of operational research, 32(3), pag. 393 – 404, 1987

[32] Ogryzek, M., Adamska-Kmiec, D., Klimach, A., *Sustainable Transport : An Efficient Transportation Network – Case Study*, Sustainability 2020,12, 8274

[33] Raicu, Ș. , *Sisteme de transport*, Editura AGIR, București, 2007, ISBN: 978-973-720-152-2

[34] Raicu, Ș., *Despre metodele de calcul a variantei optime a planului de formare a trenurilor*, Revista Căilor Ferate nr.8, 1963

[35] Raicu, Ș., Costescu, D., *Mobilitate. Infrastructuri de trafic*, Editura AGIR, București, 2020

[36] Raicu Ș., Costescu D., *Model probabilistic pentru dimensionarea depozitelor*, în volumul „*Concepte intermodale în transporturi – Lucrările seminarului proiectului IM7Danube*", Cuncev I. (Coord.), Editura AGIR, Bucureşti, 2006, ISBN 973-720-045-4, pag. 201 – 208

[37] Raicu, Ș., Costescu, D., Burciu, Ș., *Distribution system with flow consolidation at the boundary of urban congested areas*, Sustainability, Vol.2, Issue 3, pag. 1 – 17, 2020

[38] Raicu, Ș., Costescu, D., Popa, M., *Analisys of the intermodal freight transport impacts on energy consumption*, Buletinul AGIR nr. 3/2012, pag. 753 – 764

[39] Raicu, Ș., Mașală, Ghe., *Transport feroviar. Funcționare. Dezvoltare. Eficiență*, Editura Științifică și Enciclopedică, București, 1981

[40] Raicu Ș., Popa M., Mocuța G., Burciu Șt., *Logistica transporturilor*, Editura AOSR, București, 2011

[41] Raicu Ș., Raicu R., Costescu Dorinela, Popa M. *City Logistics with Collaborative Centers*, Chapter in Taniguchi E., Thompson R.G. (Eds.), City Logistics 1: New Opportunities and Challenges, ISTE Wiley, pag. 231 – 250, 2018

[42] Rodrigue, J., *The Geography of Transport Sytems*, Editura ROUTLEDGE, USA, New York, 456 pag, 2020, ISBN 978-0-367-36463-2

[43] Roşca, E., Raicu, Ş., *Optimizarea manipulării containerelor în terminale de transport*, , în volumul „*Concepte intermodale în transporturi – Lucrările seminarului proiectului IM7Danube*”, Cuncev I. (Coord.), Editura AGIR, Bucureşti, 2006, ISBN 973-720-045-4, pag.227 – 232

[44] Săndulescu, I., *Planul de formare a trenurilor de marfă*, Editura Transporturilor și Telecomunicațiilor, 1965

[45] Schönemann, R., *Scheduling rail freight node operations through a slot allocation approach*, PhD Thesis, TU Berlin, 2016

[46] Shafia, M. A., Sadjadi, S. J., & Jamili, A., Robust train formation planning. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 224(2), pag. 75 – 90, 2010

[47] **Stere, A. Ș.**, *Configurarea rețelelor hub-and-spoke în transporturile terestre*, Tendinţe ale cercetării ştiinţifice în ingineria transporturilor vol. 2/ coord.: Mihaela Popa, Vasile Dragu, Dorinela Costescu, Editura Politehnica Press, București, 2020, ISBN 978-606-515-942-6

[48] **Stere, A. Ș,** Roman, E. A., *Distribution of resources for equipping handling fronts in rail consolidation terminal*, IOP Conf. Series: Materials Science and Engineering, Volume 1037, Issue 1, 2021

[49] **Stere, A. Ș**, *Train formation plan on hub–and–spoke network configuration*, UPB Scientific Bulletin, Series D, Vol. 83, Iss. 2, 2021, ISSN 1454-2358

[50] **Stere, A. Ș.**, Olteanu, S., *Mathematical framework for determing optimal variant of train formation plan*, Solid State Technology, Vol. 63, No.6, pag.19359 – 19368, 2020

[51] Stînga, V.G., *Rețele de transport intermodal*, Teză de doctorat, București, 2018

[52] Troche, G., *Activity – Based Rail Freight Costing : A model for calculating transport costs in different production systems*, Doctoral Thesis in Railway Traffic Planning, Stockholm, Sweden 2009

[53] Xiao, J., Lin, B., *Comprehensive optimization of the one-block and two-block train formation plan*, Journal of Rail Transport Planning & Management, Volume 6, Issue 3, pag. 218 – 236, December 2016

[54] Yaghini, M., Momeni, M., Sarmadi, M., *An improved local branching approach for train formation planning*, Appl. Math. Modell., 37 (4), pag. 2300 – 2307, 2013

[55] Yaghini, M., Momeni, M., Sarmadi, M., *Solving train formation problem using simulated annealing algorithm in a simplex framework*, Journal of Advanced Transport, Volume 48, Issue 5, August 2014, pag. 402 – 416

[56] Zabihi, A., Gharakhani, M., *A literature survey of hub location problems and methods with emphasis on the marine transportations*, Uncertain Supply Chain Management 6, pag. 91–116, 2018

[57] Zgonc, B., Tekavčič, M., Jakšič, M., *The impact of distance on mode choice in freight transport*. European Transport Research Review, 11(1) 10, 2019

[58] Zhu, E., Crainic, T.G., Gendreau, M., *Scheduled Service Network Design for Freight Rail Transportation*, Operation Research, Vol.62, No.2, pag. 383 – 400, 2014