

Article

Substantiating the Logistics Chain Structure While Servicing the Flow of Requests for Road Transport Deliveries

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Abstract: The selection of the delivery scheme is one of the most complicated problems and the results of its solution condition the sustainable development of the whole market of transportation services. Freight forwarders should consider numerous random parameters characterizing demand and technological processes to choose the proper structure of the logistics chain. The paper aims to propose a method for choosing the logistics chain structure, based on the analysis of the total expenses as a function from the demand parameters characterizing stochastic variables of the consignment weight, the delivery distance, and the time interval between the requests in the flow of queries for cargo delivery. Four basic logistics chain structures, widely used on road transport, are described to demonstrate the selection process. The areas of the most efficient use of the logistics chain structures can be defined for the flow of requests for cargo deliveries. The paper shows such areas on the example of goods delivery by automobile transport. Determining the areas of the most efficient use of the specific logistics chain structures contributes to the effective choice of correct delivery variants by freight forwarders.

Keywords: logistics chain structure; total expenses; demand parameters; requests flow

1. Introduction

The process of cargo delivery is a complex stochastic process, due to the influence of a large number of random factors on technological operations. The processes of interaction between enterprises at the transportation market are organized by freight forwarders, therefore the efficiency of the forwarding technological process fully determines the sustainable development of the transportation market as the macro-logistics system. Selecting the logistics chain structure is one of the main problems being solved by freight forwarders, which ensures minimal expenses of the delivery process participants. The results of this problem-solving process significantly influence the sustainable development of the transportation market as a macro logistics system.

Substantiating the logistics chain structure is usually considered as a part of a more sophisticated task—designing the supply chain. The recent literature describes that task as a complicated procedure involving numerous subtasks at different levels of the decision-making process. The logistics chain represents the successive steps that are being implemented to achieve the process goal whether it is a product manufacturing or goods delivery. In the case of the goods delivery, these steps are defined by the involved transportation market entities and the logistics chain structure can be described by the used delivery scheme as a sequence of these entities. The supply chain is a more complicated system, being defined as the sequence of sub-processes that are related to the production and distribution of goods. However, the logistics chain structure can be considered as the backbone of the supply chain

design and a crucial factor defining the supply chain efficiency. Carvalho and Fonseca (2017) state that the proper logistics structure is the key factor of competitiveness [1].

Melnyk et al. (2014) propose a framework of supply chain design that comprehends business and political environment, the supply chain lifecycle, behavioral, and structural design elements that define a supply chain, and technological operations being implemented within a supply chain [2]. Blos et al. (2018), in their framework for the supply chain design, underline that the carrier viewpoint should be considered in the designing process [3]. According to Yao and Askin (2019), the decision-making procedures concerning the product and supply chain design should be jointly developed [4], which increases the design complexity, but might result in the optimal decision. Bányai et al. underline the impact of routing procedures on environmental awareness and sustainability [5] and the influence of the scheduling outcome on energy efficiency [6]. Calleja et al. (2018) provide a review of methodological approaches to supply chain design and conclude that the use of typical solutions for supply chains designing is not the proper approach, while the methods proposing a succession of stages to follow through the design process may be effective if they are clear for practitioners [7]. The facility location is another issue to be considered while designing the supply chain structure [8]; however, in terms of the problem of choosing the logistics chain structure, the location of facilities only influences the constant operational costs used as initial data while solving the problem. A number of authors also pay significant attention to the consideration of the random nature of demand and technological processes [9,10], which results in the appearance of risk factors [11–13].

Sustainability issues that are related to the supply chain design problem are widely discussed in the recent scientific literature. Moreno-Camacho et al. (2019) state that increasing pressure from governments and other different groups of stakeholders has motivated the study of sustainability assessment in the supply chain context [14]. Three pillars of the system development, i.e., economic, environmental, and social, should be considered in the process of a supply chain design, according to the sustainable development paradigm. These directions are highlighted in a number of publications that are devoted to the design and implementation of sustainable supply chains [15–18].

While solving the problems that are related to optimization of the logistics chain structure, the authors use criteria corresponding to the mentioned directions of sustainable development: the authors of the paper [15] propose minimizing the total cost as economic issue, minimizing the total amount of CO₂ emission as environmental issue, and maximizing the total social influence as social issue; Sherafati et al. (2019) maximize profit primarily while capturing social development by prioritizing the less developed regions and dealing with ecological aspect by using environmentally friendly transport facilities [16]. Accordingly, optimization problems that are related to sustainable supply chain design are solved as multi-objective problems [15–18]. The authors of the paper [14] have analyzed more than 100 papers, including documents studying supply chains, and came up with the conclusion that modern literature emphasizes the environmental aspects of the supply chain design, but does not pay much attention to social criteria. It should be noted that the commonly used efficiency criterion that allows for considering three directions of sustainable development is the total costs, which include all of the losses and expenses related to environmental and social issues [19–21].

The optimization methods used in the recent publications vary from certain methods (augmented ϵ -constraint method [18], robust programming [16]) to the methods, where heuristics should be used to obtain a solution (hybrid genetic algorithm [15], mixed-integer linear programming model [20]).

The current paper contributes to the structural design of the supply chain by defining the optimal (within the given set of alternatives) solution for the delivery scheme. The decision regarding the structure of the logistics chain is being made while considering the viewpoint of all the transport market entities participating in the delivery process; the implications of this decision define the sustainable development of the whole macro-logistics system. Additionally, in the method that was proposed by this paper, the demand parameters are taken into consideration as the characteristics of the flow of requests for transport services. Consequently, the areas of the most efficient use of the delivery schemes can be established for the considered demand parameters. In that way, while choosing the proper

structure of the logistics chain, the decision-maker (e.g., freight forwarder) will obtain the answer by applying the consignment parameters as arguments, without implementing the time-consuming procedures of the evaluation of the costs for all the alternative structures.

2. Methodology

The structure of the logistics chain (LC) describes the structure of the technological process of cargo delivery, which reflects the sequence of participants in the delivery process of various entities at the transport services market. It is necessary to distinguish the problem of choosing the optimal LC variant and the problem of substantiating the optimal carrier (an operator, a contractor for performing certain types of work, etc.) or the optimal delivery route. The choice of the LC structure should be justified before making a decision on participation in the delivery process of a specific transportation market entity, since it refers to the task of management at the macro-level.

2.1. Problem Statement

Figure 1 presents the process of choosing the optimal LC as a cybernetic model. A set of incoming parameters is described by the numerical characteristics of a request for a consignment for delivery—its weight Q , the delivery distance L , and the interval I of the request arrival [22,23]. The influence of environmental factors is described by the values of parameters $\{T\}$, characterizing the technological processes of the LC entities, in the mathematical model, these parameters are realizations of random variables of the delivery speed, the time of specific technological operations, non-production vehicle downtime, etc. The result of the choice is such the structure LC_{opt} , for which the value of the considered efficiency criterion is optimal.

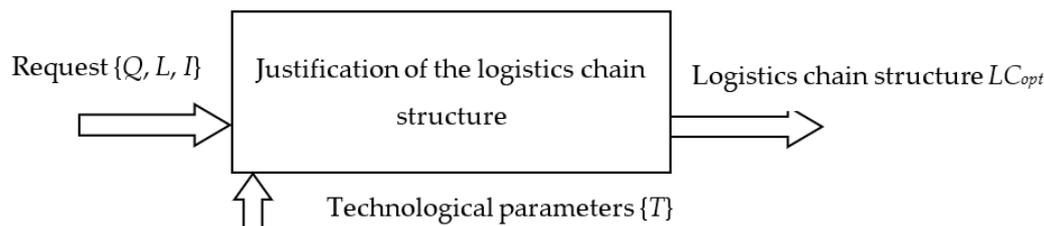


Figure 1. Model for choosing the optimal logistics chain (LC) structure.

When solving problems at the macro-logistical level, it is advisable to use the total costs of the entities that form the LC as the efficiency criterion (this indicator is considered as the objective function in [19,20,24,25], and is also used as a sub-criterion in [26,27]). In this case, the problem of choosing the optimal LC structure can be formalized, as follows:

$$LC_{opt} = \arg \min_{LC} E_{\Sigma i}, \quad (1)$$

where: $E_{\Sigma i}$ is the total costs of entities within the logistics chain.

In this case, the total costs are functionally determined by a set of input parameters and the parameters describing the influence of the external environment:

$$E_{\Sigma} = f(LC, \{Q, L, I\}, \{T\}). \quad (2)$$

Mandatory elements of the LC are the consignor FO^A and the consignee FO^B . The LC also contains at least one forwarder and one carrier. Cargo terminals may also be included in complex LC with the participation of several carriers and freight forwarders. A customs point should be considered in the case of international delivery of goods, as a specific element, the presence of which determines the cost

structure for other participants in the supply chain. In general, the LC structure can be formalized, as follows:

$$LC = \{FO^A; \{C\}; \{FT\}; \{FF\}; FO^B; CP\}, \tag{3}$$

where $\{C\}$ is the set of carriers; $\{FT\}$ is the set of cargo terminals; $\{FF\}$ is the set of freight forwarders; and, CP is the customs point.

While using the above formulation of the problem, in general, the methodology for selecting the optimal LC structure can be defined as the sequential implementation of three stages:

1. The formation of alternative LC variants, determining the structure of the technological scheme. Alternatives are determined on the basis of the availability of cargo terminals, customs points, as well as partner forwarders operating in the appropriate geographic area.
2. The efficiency evaluation for a set of alternative structures. The assessment is carried out on the basis of average market value indicators, while taking the random nature of technological parameters into account. The result of the evaluation for each LC variant is a random value of the efficiency criterion.
3. The selection of the optimal LC structure and subsequent measures related to the determination of the LC participants and the development of specific technological processes. The choice of the optimal LC structure is carried out on the basis of a comparative assessment of characteristics of random variables that describe the effectiveness criterion for each alternative structure. For the presented formulation of the problem (1), the choice is made according to the minimum expected value of the total costs.

While choosing the optimal LC variant, alternative structures can be preliminarily eliminated if additional preferences of customers in terms of delivery time and quality of service are known.

2.2. Basic Alternative Variants of the Logistics Chains' Structure

The choice of the best LC structures is carried out on a set of alternatives. Let us consider the basic variants of the LC structures for goods delivery by road transport.

For an individual LC as a part of a logistics system, the initial element generating the material flow is the cargo owner (consignor), and the final element is the other cargo owner (consignee). Accordingly, the initial and final elements in the supply chain are freight owners. Physically, a carrier performs the processing of the material flow. The organization of the material flow processing is implemented by a freight forwarder using, if necessary, the resources of cargo terminals. As an organizer of the technological processes, a freight forwarder is an element of LC, which concentrates information flows. Since the freight owner, in order to fulfill his need in goods delivery, addressing the freight forwarder, the cash flow in the LC passes initially from the owner to the freight forwarder, and then to the other participants in the chain.

Figure 2 presents the simplest version of LC. The presence of the CP element in the LC structure is marked by a dotted line, since this element is only present in the case of international delivery of goods.

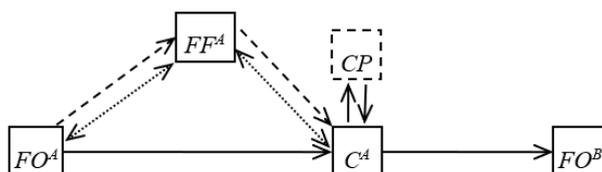


Figure 2. The simplest variant of the LC structure.

Formally, the simplest supply chain LC^{1F} is a collection of elements of the following type:

$$LC^{1F} = \{FO^A; C^A; FF^A; FO^B; CP\}, \tag{4}$$

where C^A is a carrier in the region of a consignor; and, FF^A is a freight forwarder in the region of a consignor.

For this option, the delivery process is coordinated by one forwarder, one carrier is involved in the transportation, and cargo terminals are not involved in the delivery process. The shipper declares his need to relocate the shipment. The freight forwarder determines a carrier who can deliver this consignment to the consignee, and then contacts the shipper, concludes bilateral agreements for arranging delivery between the freight forwarder and the shipper, and also between the freight forwarder and the carrier. The shipper pays the freight forwarder's services; from the amount that was received from the customer, the freight forwarder pays for the carrier's services. The carrier delivers a shipment from the shipper to the border, and then from the customs point to the consignee. This version of LC is typical for the delivery of goods by road transport when the consignment weight equals the vehicle capacity.

A more complicated version is the LC variant with the participation of two freight forwarders and, accordingly, of two carriers (Figure 3).

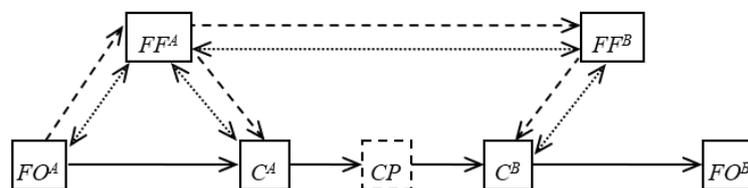


Figure 3. The LC structure with two forwarders.

Such a variant of LC (LC^{2F} -type chain) is the following set of elements:

$$LC^{2F} = \{FO^A; C^A; FF^A; FO^B; C^B; FF^B; CP\}, \quad (5)$$

where C^B is a carrier in the region of a consignee; and, FF^B is a freight forwarder in the region of a consignee.

After receiving the request from a shipper, a freight forwarder finds a carrier for the delivery of the consignment to the border, and also sends the request to the partner forwarder. The partner forwarder organizes the delivery of a consignment from the border to the consignee, while using a regional carrier. In such a situation, four bilateral agreements are signed: between the freight forwarder and the shipper, between the freight forwarder and the carrier, between two freight forwarders, and also between the foreign freight forwarder and the foreign carrier. In this case, the shipper will pay for the services of the first forwarder, which of the received reward will pay for the services of the regional carrier, as well as the services of the foreign forwarder. A partner forwarder pays for carrier services in his region from the received remuneration.

The cargo terminal is involved in the process of processing the material flow in the LC version that is presented in Figure 4.

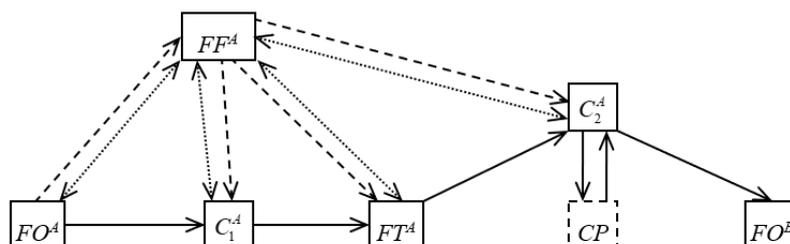


Figure 4. The LC structure with one terminal.

This variant of the logistics chain (LC^{1T} -type chain) is a combination of seven basic elements:

$$LC^{1T} = \{FO^A; C_1^A; C_2^A; FF^A; FT^A; FO^B; CP\}, \quad (6)$$

where C_1^A is a carrier in the consignor's region ensuring the delivery of cargo to the terminal; C_2^A is a carrier in the consignor's region providing international delivery; and, FT^A is a cargo terminal in the consignor's region.

After receiving the request from the freight owner, the freight forwarder assesses the feasibility of delivering a shipment through the cargo terminal. If this variant of the chain structure is economically feasible, then the forwarder searches for carriers for delivering cargo to the terminal and for directly exporting the enlarged shipment for delivery to the consignee. Four bilateral agreements are signed after determining the parties of the shipment process: between the forwarder and the shipper, between the forwarder and the regional carrier, between the forwarder and the cargo terminal, and between the forwarder and the international carrier. Of the funds that are received by the freight forwarder from the freight owner, the forwarder pays for the services of carriers and the cargo terminal. This variant of the LC is used when a consignment is delivered to the terminal by automobile transport, consolidation of shipments by directions, and subsequent delivery by the main transport (e.g., by the rail carrier). It is also possible that the cargo terminal organizes the export of the enlarged shipment, acting as a 4PL-provider.

A more common option for the delivery with the participation of the main transport is the variant of a logistics chain structure with two terminals (Figure 5).

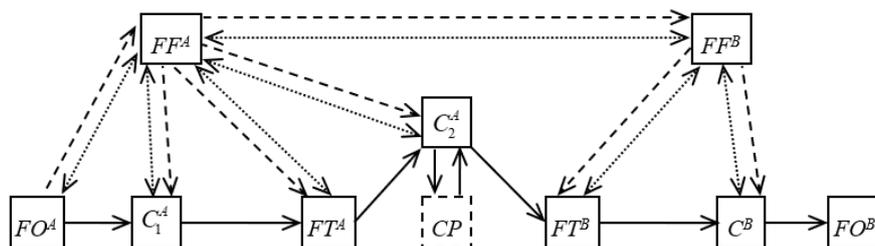


Figure 5. The LC structure with two terminals.

The two-terminal LC variant LC^{2T} is the following set of elements:

$$LC^{2T} = \{FO^A; C_1^A; C_2^A; FF^A; FT^A; FO^B; FF^B; C^B; FT^B; CP\}, \quad (7)$$

where FT^B is a cargo terminal in the consignee's region.

In this case, the freight owner declares its need to deliver a consignment. The freight forwarder, having received the request, concludes that of the many alternative options for the logistics chain structure, the option with two cargo terminals will be the most effective one. After that, the freight forwarder determines the regional carrier for the delivery of the shipment from the shipper to the terminal, concludes an agreement with the terminal and the main carrier, and then also sends a request for the delivery of the shipment to a foreign partner forwarder. The partner forwarder organizes the delivery of the consignment from a terminal in his region to the consignee. For this, it determines the regional carrier and enters into an agreement with the terminal. For this LC variant, the following agreements are signed: in the consignor region—between the freight forwarder and the cargo owner, between the forwarder and the regional carrier, between the forwarder and the cargo terminal in the sender's region, and between the forwarder and the international carrier; in the consignee region—between the forwarder and the cargo terminal in the recipient region, between the forwarder and the regional carrier; also, a contract is concluded between the two forwarders. The freight forwarder in the sender region from the remuneration received from the freight owner pays for the services of regional and international carriers, the terminal in his region, as well as the partner

forwarder services. The freight forwarder in the recipient region pays for the services of the terminal and the carrier in its region from the funds that are received from the first freight forwarder. It is also possible that the terminal pays the carrier's services in the sender's region, and the carrier's services for delivering the consignment to the consignee are paid by the freight terminal in the recipient's region.

The situations, reviewed in Figures 2–5, can be used as the basic variants for the LC structures. It is worth mentioning that the LC structure should be specified while taking the type of connection into account (for international transportation, a customs point is included in the LC). The alternative LC variants are also considered while taking the availability of cargo terminals and partner forwarders in the regions of delivery into account.

2.3. Evaluating the Effectiveness of the Logistic Chain Structures

Following the accepted criterion of the effectiveness, its main partials are the expenses of the corresponding LC subjects.

Possible cost items for a freight forwarder as an organizer of the delivery process are:

- costs of finding a client;
- costs associated with the preparation of documentation for the delivery of a shipment from a consignor to a consignee;
- costs of finding a carrier, partner forwarder (if appropriate), 3PL-provider (if appropriate);
- costs of the organization and implementation of loading and unloading processes;
- costs of the carrier (carriers) services;
- expenses for payment of the 3PL-provider (providers) services;
- customs payments; and,
- tax deductions.

The main items of costs for a freight owner are:

- costs of forming a transport package;
- losses due to freezing of funds that constitutes the shipment value; and,
- payment for the services of forwarders.

The carrier, providing the process of transportation of a consignment, is characterized by the following cost items:

- direct costs of delivery operations;
- costs of idle time under loading and unloading;
- costs of idle time in the customs point; and,
- tax deductions.

Freight terminals, performing the main function of consolidation and disaggregation of consignments, are characterized by the following costs:

- costs of transshipment (unloading and loading);
- costs of the formation and disbandment of transport packages;
- costs of interim storage operations;
- tax deductions.

We obtain the sum of the costs for the elements of the chain while considering the efficiency criterion at the LC level:

$$E_{LC}^{1F} = E_{FO}^A + E_C^A + E_{FF}^A + E_{FO}^B, \quad (8)$$

$$E_{LC}^{2F} = E_{FO}^A + E_C^A + E_{FF}^A + E_{FO}^B + E_C^B + E_{FF}^B, \quad (9)$$

$$E_{LC}^{1T} = E_{FO}^A + E_{C1}^A + E_{C2}^A + E_{FF}^A + E_{FT}^A + E_{FO}^B, \quad (10)$$

$$E_{LC}^{2T} = E_{FO}^A + E_{C1}^A + E_{C2}^A + E_{FF}^A + E_{FT}^A + E_C^B + E_{FF}^B + E_{FT}^B + E_{FO}^B. \quad (11)$$

where E_{LC}^{1F} , E_{LC}^{2F} , E_{LC}^{1T} , and E_{LC}^{2T} are the total costs for 1F-, 2F-, 1T-, and 2T-variants of the LC structure (EUR).

Appendix A presents the proposed methodology for calculation of the expenses for the logistics chain participants.

3. Results

The functional dependence of the effectiveness criterion on the parameters of the flow of requests for transport services is substantiated in Appendix B on the basis of the used methodology for the total expenses' calculation. To substantiate this, the costs of LC elements are defined as a function of the requests flow parameters, i.e., in fact—to present the costs of the j -th participant for servicing of the i -th request in the form $E_j = f(Q_i, L_i, I_i)$.

For the described LC structures, the total costs of all the participants of the delivery process Equations (8)–(11), while considering the resulting functional dependencies, take the following form:

$$E_{LC}^{1F} = a_0^{1F} + a_{Q2}^{1F} \cdot Q^2 + a_{QL}^{1F} \cdot Q \cdot L + a_Q^{1F} \cdot Q + a_I^{1F} \cdot I + a_L^{1F} \cdot L; \quad (12)$$

$$E_{LC}^{2F} = a_0^{2F} + a_{Q2}^{2F} \cdot Q^2 + a_Q^{2F} \cdot Q + a_I^{2F} \cdot I + a_{QL}^{2F} \cdot Q \cdot L + \{a_L^{CA} \cdot L^A + a_L^{CB} \cdot L^B\} + Q \cdot \{a_{QL}^{CA} \cdot L^A + a_{QL}^{CB} \cdot L^B\}; \quad (13)$$

$$E_{LC}^{1T} = a_0^{1T} + a_{Q2}^{1T} \cdot Q^2 + a_{QL}^{1T} \cdot Q \cdot L + a_Q^{1T} \cdot Q + a_I^{1T} \cdot I + \{a_L^{CA} \cdot L^A + a_L^{CB} \cdot L^B\} + Q \cdot \{a_{QL}^{CA} \cdot L^A + a_{QL}^{CB} \cdot L^B\}; \quad (14)$$

$$E_{LC}^{2T} = a_0^{2T} + a_{Q2}^{2T} \cdot Q^2 + a_{QL}^{2T} \cdot Q \cdot L + a_Q^{2T} \cdot Q + a_I^{2T} \cdot I + \{a_L^{CA1} \cdot L^{A1} + a_L^{A2} \cdot L^{A2} + a_L^B \cdot L^B\} + Q \cdot \{a_{QL}^{CA1} \cdot L^{A1} + a_{QL}^{CA2} \cdot L^{A2} + a_{QL}^B \cdot L^B\}, \quad (15)$$

where a_0^j , a_{Q2}^j , a_{QL}^j , a_Q^j , a_I^j , and a_L^j are the coefficients of the functional dependency of the total costs from the request parameters for the j -th LC structure;

L^{A1} , L^{A2} , L^A , and L^B are the delivery distances covered by carriers in the sender region (L^{A1} , L^{A2} , or L^A) and in the recipient region (L^B) (km).

The coefficients for the dependency (12) are determined, as follows:

$$\begin{cases} a_0^{1F} = a_0^{FO} + a_0^C + a_0^{FF}, \\ a_{Q2}^{1F} = a_{Q2}^{FO}, \\ a_{QL}^{1F} = a_{QL}^{FO} + a_{QL}^C, \\ a_Q^{1F} = a_Q^{FO} + a_Q^C, \\ a_I^{1F} = a_I^{FO} + a_I^{FF}, \\ a_L^{1F} = a_L^C. \end{cases} \quad (16)$$

For the dependency of the total costs of participants in the 2F-structure of LC, the coefficients are determined by the following formulas:

$$\begin{cases} a_0^{2F} = a_0^{FO} + a_0^{CA} + a_0^{CB} + a_0^{FFA} + a_0^{FFB}, \\ a_{Q2}^{2F} = a_{Q2}^{FO}, \\ a_{QL}^{2F} = a_{QL}^{FO}, \\ a_Q^{2F} = a_Q^{FO} + a_Q^{CA} + a_Q^{CB}, \\ a_I^{2F} = a_I^{FFA} + a_I^{FO}. \end{cases} \quad (17)$$

For Equation (14), which is used for estimations of the total costs for the 1T-variant of LC, the coefficients are calculated in the following way:

$$\begin{cases} a_0^{1T} = a_0^{FO} + a_0^{CA} + a_0^{CB} + a_0^{FF}, \\ a_{Q2}^{1T} = a_{Q2}^{FO}, \\ a_{QL}^{1T} = a_{QL}^{FO}, \\ a_Q^{1T} = a_Q^{FO} + a_Q^{CA} + a_Q^{CB} + a_Q^{FT}, \\ a_I^{1T} = a_I^{FO} + a_I^{FF}. \end{cases} \quad (18)$$

The coefficients for the model of the total costs for participants of 2T-variant of LC are defined on the basis of the following dependencies:

$$\begin{cases} a_0^{2T} = a_0^{FO} + a_0^{CA1} + a_0^{CA2} + a_0^{CB} + a_0^{FFA} + a_0^{FFB}, \\ a_{Q2}^{2T} = a_{Q2}^{FO}, \\ a_{QL}^{2T} = a_{QL}^{FO}, \\ a_Q^{2T} = a_Q^{FO} + a_Q^{CA1} + a_Q^{CA2} + a_Q^{CB} + a_Q^{FTA} + a_Q^{FTB}, \\ a_I^{2T} = a_I^{FO} + a_I^{FFA}. \end{cases} \quad (19)$$

Appendix B shows formulas for calculating the coefficients used in definitions Equations (16)–(19).

It should be noted that the delivery distance that is covered by various carriers for the considered LC variants is determined based on the parameter L . Thus, for the 2F- and 1T-structures, the following condition is fulfilled:

$$L = L^A + L^B, \quad (20)$$

and for 1T-structure of LC:

$$L = L^{A1} + L^{A2} + L^B. \quad (21)$$

As can be seen from 12–15, the total costs of participants in LC quadratically depend on the consignment weight and linearly on the delivery distance and the request receipt interval. If in the considered range of the parameter of the request, there is a point of intersection of a pair of functions from 12–15, and then there exists the areas of preferred use of the corresponding LC structures.

Let us define the area of the most efficient use of the j -th LC structure, as such values of the request parameter ω , for which the considered variant of LC is optimal (is characterized by the minimum value of total costs):

$$\Omega_j = [\omega_l; \omega_u] \Leftrightarrow \omega = \operatorname{argmin}_j E_{\Sigma}^j(\omega), \quad \forall \omega \in [\omega_l; \omega_u], \quad (22)$$

where Ω_j is the area of the most efficient use of the j -th LC structure; and, ω_l and ω_u are the lower and upper bounds of the area of the most efficient use.

4. Discussion

Figure 6 shows the dependence of the total costs of the LC participants from the consignment weight for the request interval equal to 96 h and the delivery distance equal to 3000 km (the values of other numeric parameters, needed to calculate the total expenses, were taken as the market averages for deliveries between Poland and Ukraine in May 2019). There are points of intersection for 1F- and 1T-variants of LC, as well as for 1T- and 2T-variants, as it can be seen from the graphs. Thus, it can be argued that, in this case, there are areas of the most efficient use for 1F-, 1T-, and 2T-variants of LC. It is sufficient to determine the roots of the equation to determine the boundaries of the areas of the most efficient use of the i -th and j -th variants of the LC

$$E_{\Sigma}^j(\omega) - E_{\Sigma}^i(\omega) = 0. \quad (23)$$

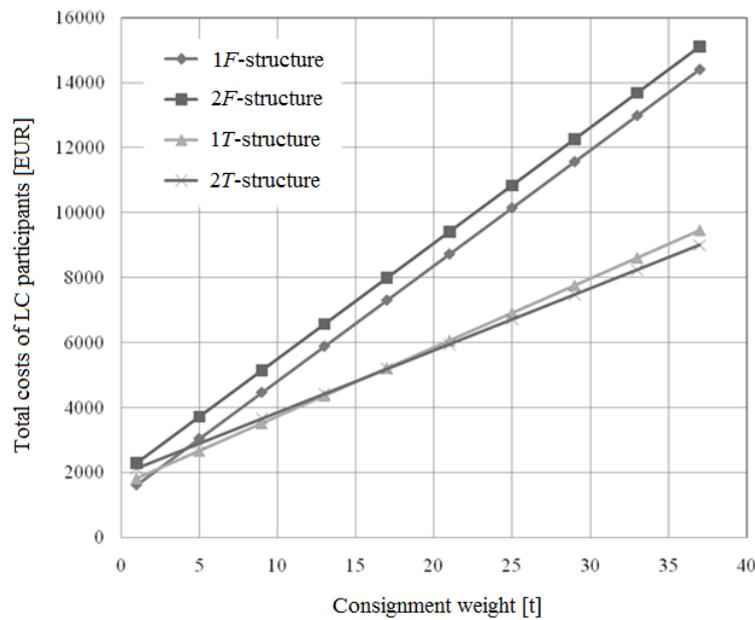


Figure 6. Dependency of the total costs of participants in the LC on the consignment weight.

Equation (23) is linear in relation to the delivery distance and the request interval, and it is squared in relation to the consignment weight.

The estimation of the areas of the most efficient use of the LC structures to justify the choice of the delivery scheme should be carried out in the following sequence:

- set the incoming requests' interval as a constant parameter (for the flow of requests, the expected value of the requests interval is taken);
- define ranges on the set of possible values of the delivery distance;
- for the accepted value of the requests' arrival interval and the upper bound of the delivery distance range, determine the roots of equation (23) for all pairs of the LC structures; and,
- the obtained solutions determine the bounds of the areas of the most efficient use of the alternative LC structures, the corresponding dependencies of the total costs form the lower polygonal chain on the graph.

For the pair of 1F- and 2F- structures, the boundaries of the area of the preferred use are determined as the roots of the following equation:

$$\begin{aligned} & (a_{Q2}^{1F} - a_{Q2}^{2F}) \cdot Q^2 + (a_{QL}^{1F} \cdot L - a_{QL}^{2F} \cdot L + a_Q^{1F} - a_Q^{2F} - a_{QL}^{CA} \cdot L^A - a_{QL}^{CB} \cdot L^B) \cdot Q + \\ & + (a_0^{1F} - a_0^{2F} + a_I^{1F} \cdot I - a_I^{2F} \cdot I + a_L^{1F} \cdot L - a_L^{CA} \cdot L^A - a_L^{CB} \cdot L^B) = 0. \end{aligned} \quad (24)$$

Similarly, the areas of preferred use are estimated for pairs of 1F and 1T variants, 1F- and 2T- variants, 2F- and 1T- variants, 2F- and 2T- variants, and 1T- and 2T- variants of LC that are based on the corresponding quadratic equations:

$$\begin{aligned} & (a_{Q2}^{1F} - a_{Q2}^{1T}) \cdot Q^2 + (a_{QL}^{1F} \cdot L - a_{QL}^{1T} \cdot L + a_Q^{1F} - a_Q^{1T} - a_{QL}^{CA} \cdot L^A - a_{QL}^{CB} \cdot L^B) \cdot Q + \\ & + (a_0^{1F} - a_0^{1T} + a_I^{1F} \cdot I - a_I^{1T} \cdot I + a_L^{1F} \cdot L - a_L^{CA} \cdot L^A - a_L^{CB} \cdot L^B) = 0; \end{aligned} \quad (25)$$

$$\begin{aligned} & (a_{Q2}^{1F} - a_{Q2}^{2T}) \cdot Q^2 + \left(a_Q^{1F} - a_Q^{2T} + a_{QL}^{1F} \cdot L - a_{QL}^{2T} \cdot L - \right. \\ & \left. - a_{QL}^{CA1} \cdot L^{A1} - a_{QL}^{CA2} \cdot L^{A2} - a_{QL}^B \cdot L^B \right) \cdot Q + \\ & + (a_0^{1F} - a_0^{2T} + a_I^{1F} \cdot I - a_I^{2T} \cdot I + a_L^{1F} \cdot L - a_L^{CA1} \cdot L^{A1} - a_L^{A2} \cdot L^{A2} - a_L^B \cdot L^B) = 0; \end{aligned} \quad (26)$$

$$(a_{Q2}^{2F} - a_{Q2}^{1T}) \cdot Q^2 + (a_Q^{2F} - a_Q^{1T} + a_{QL}^{2F} \cdot L - a_{QL}^{1T} \cdot L) \cdot Q + (a_0^{2F} - a_0^{1T} + a_I^{2F} \cdot I - a_I^{1T} \cdot I) = 0; \tag{27}$$

$$(a_{Q2}^{2F} - a_{Q2}^{2T}) \cdot Q^2 + \left(a_Q^{2F} - a_Q^{2T} + a_{QL}^{2F} \cdot L - a_{QL}^{2T} \cdot L + a_{QL}^{CA} \cdot LA - a_{QL}^{CA1} \cdot LA1 - a_{QL}^{CA2} \cdot LA2 \right) \cdot Q + (a_0^{2F} - a_0^{2T} + a_I^{2F} \cdot I - a_I^{2T} \cdot I + a_L^{CA} \cdot LA - a_L^{CA1} \cdot LA1 - a_L^{CA2} \cdot LA2) = 0; \tag{28}$$

$$(a_{Q2}^{1T} - a_{Q2}^{2T}) \cdot Q^2 + \left(a_Q^{1T} - a_Q^{2T} + a_{QL}^{1T} \cdot L - a_{QL}^{2T} \cdot L + a_{QL}^{CA} \cdot LA - a_{QL}^{CA1} \cdot LA1 - a_{QL}^{CA2} \cdot LA2 \right) \cdot Q + (a_0^{1T} - a_0^{2T} + a_I^{1T} \cdot I - a_I^{2T} \cdot I + a_L^{CA} \cdot LA - a_L^{CA1} \cdot LA1 - a_L^{CA2} \cdot LA2) = 0. \tag{29}$$

Since, according to Equations (16)–(19) $a_{Q2}^{1F} = a_{Q2}^{2F} = a_{Q2}^{1T} = a_{Q2}^{2T} = a_{Q2}^{FO}$, the factors for Q^2 in the Equations (24)–(29) are equal to 0. Thus, the presented quadratic equations degenerate to linear, which indicates the presence of, at most, one intersection point on the graphs of total costs corresponding to the considered LC structures. The boundaries Q_{i-j} of preferred use areas for the i -th and j -th structures of the LC, in this case, are determined on the basis of the following expressions:

$$Q_{1F-2F} = \frac{a_0^{2F} - a_0^{1F} + a_I^{2F} \cdot I - a_I^{1F} \cdot I + a_L^{CA} \cdot LA - a_L^{1F} \cdot L + a_L^{CB} \cdot LB}{a_Q^{1F} - a_Q^{2F} + a_{QL}^{1F} \cdot L - a_{QL}^{2F} \cdot L - a_{QL}^{CA} \cdot LA - a_{QL}^{CB} \cdot LB}; \tag{30}$$

$$Q_{1F-1T} = \frac{a_0^{1T} - a_0^{1F} + a_I^{1T} \cdot I - a_I^{1F} \cdot I + a_L^{CA} \cdot LA - a_L^{1F} \cdot L + a_L^{CB} \cdot LB}{a_Q^{1F} - a_Q^{1T} + a_{QL}^{1F} \cdot L - a_{QL}^{1T} \cdot L - a_{QL}^{CA} \cdot LA - a_{QL}^{CB} \cdot LB}; \tag{31}$$

$$Q_{1F-2T} = \frac{a_0^{2T} - a_0^{1F} + a_I^{2T} \cdot I - a_I^{1F} \cdot I - a_L^{1F} \cdot L + a_L^{CA1} \cdot LA1 + a_L^{A2} \cdot LA2 + a_L^B \cdot LB}{a_Q^{1F} - a_Q^{2T} + a_{QL}^{1F} \cdot L - a_{QL}^{2T} \cdot L - a_{QL}^{CA1} \cdot LA1 - a_{QL}^{CA2} \cdot LA2 - a_{QL}^B \cdot LB}; \tag{32}$$

$$Q_{2F-1T} = \frac{a_0^{1T} - a_0^{2F} + a_I^{1T} \cdot I - a_I^{2F} \cdot I}{a_Q^{2F} - a_Q^{1T} + a_{QL}^{2F} \cdot L - a_{QL}^{1T} \cdot L}; \tag{33}$$

$$Q_{2F-2T} = \frac{a_0^{2T} - a_0^{2F} + a_I^{2T} \cdot I - a_I^{2F} \cdot I + a_L^{CA1} \cdot LA1 - a_L^{CA} \cdot LA + a_L^{A2} \cdot LA2}{a_Q^{2F} - a_Q^{2T} + a_{QL}^{2F} \cdot L - a_{QL}^{2T} \cdot L + a_{QL}^{CA} \cdot LA - a_{QL}^{CA1} \cdot LA1 - a_{QL}^{CA2} \cdot LA2}; \tag{34}$$

$$Q_{1T-2T} = \frac{a_0^{2T} - a_0^{1T} + a_I^{2T} \cdot I - a_I^{1T} \cdot I + a_L^{CA1} \cdot LA1 - a_L^{CA} \cdot LA + a_L^{A2} \cdot LA2}{a_Q^{1T} - a_Q^{2T} + a_{QL}^{1T} \cdot L - a_{QL}^{2T} \cdot L + a_{QL}^{CA} \cdot LA - a_{QL}^{CA1} \cdot LA1 - a_{QL}^{CA2} \cdot LA2}. \tag{35}$$

The areas of the most efficient use of the LC structures, as shown in Table 1, were obtained using the method described above based on Equations (30)–(35) for the expected value of the request interval equal to 2 h. The presented numeric results should be understood as an example describing the principle of justification of the best possible solution for the LC structure.

Table 1. Areas of the most efficient use of LC structures for deliveries by road transport.

Delivery Distance	1F-Structure	2F-Structure	1T-Structure	2T-Structure
up to 300 km	up to 3 tons	-	3 ... 122 tons	more than 122 tons
301 ... 500 km	up to 3 tons	-	3 ... 31 tons	more than 31 tons
501 ... 700 km	up to 3 tons	-	3 ... 23 tons	more than 23 tons
701 ... 900 km	up to 2 tons	-	2 ... 20 tons	more than 20 tons
901 ... 1100 km	up to 2 tons	-	2 ... 19 tons	more than 19 tons
1101 ... 1300 km	up to 2 tons	-	2 ... 18 tons	more than 18 tons
more than 1300 km	up to 2 tons	-	2 ... 17 tons	more than 17 tons

While analyzing the numerical results of the assessment of the areas of the most efficient use for considered ranges of demand parameters, the following implications must be mentioned:

- the use of the simplest version of the LC is optimal for the delivery by road transport of small consignments (up to three tons);
- the use in road transport of the LC variant with the participation of two freight forwarders is not characterized by the lowest possible total costs regardless of the values of the consignment weight and the delivery distance; therefore, the 2F-variant of the LC should only be used in cases when it is not possible to arrange delivery without the participation of the contractor forwarder; and,
- the bounds of the areas of the most effective LC structures (for the consignment volume as a parameter) inversely depend on the delivery distance.

Figure 7 shows the pattern of changes in the boundary of the areas of the most efficient use for 1T- and 2T-variants of the LC for the example considered in Table 1: the lesser the consignment weight, the bigger the delivery distance should be for 2T-structure to appear the better option in terms of the total costs.

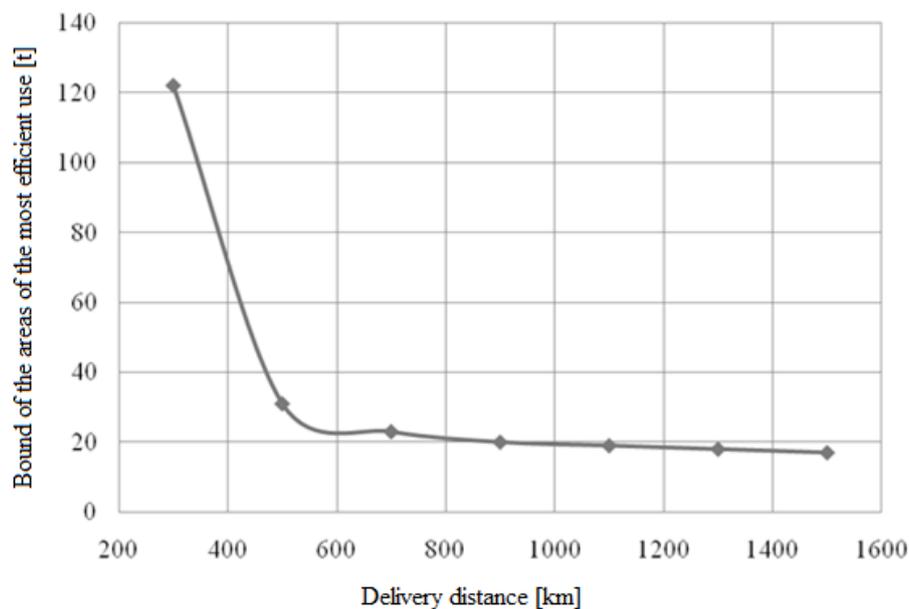


Figure 7. Dependence of the boundary value of the areas of the most efficient use of 1T- and 2T-structures on the delivery distance.

The obtained dependency allows for us to conclude that the use of the LC with the participation of two freight terminals for short delivery distances is only advisable if the consignment weight is big enough (more than 100 tons). Additionally, vice versa—when the delivery distance is more than 500 km, the bound of the area of the most efficient use for the 2T-structure corresponds to a delivery weight of about 20 tons.

The proposed method for justification of the areas of the most efficient use for the considered variants of the LC structures has a significant practical value. The following managerial implications regarding the supply chain management procedures should be highlighted:

- having the areas substantiated for the given demand parameters, decision-makers (freight forwarders or other logistics operators) can choose the proper LC structure without calculating the costs for all possible alternative structures;
- the proposed methodology contributes to decreasing of the clients servicing time and reduces possible mistakes made by operators while making a decision concerning the LC structure, and in total – supports the sustainable operation of transport on a regional scale; and,

- the areas of the most efficient use of the LC structures can be implemented in specialized tools of information systems supporting decisions of logistics operators.

5. Conclusions

The selection of the optimal variant for the delivery of goods by road transport should be made on the basis of the minimum total costs of the LC participants—freight owners, carriers, freight forwarders, and freight terminals. The total costs of the LC participants are functionally determined by the structure of the chain, the parameters of the demand for transport services, and the parameters describing the impact on the LC of the external environment.

The structure of a LC for the delivery of goods by road transport can be assigned to one of the following options: *1F* is the simplest structure with one forwarder, *2F* is delivery with the participation of two forwarders without the involvement of freight terminals, *1T* is delivery of a consignment through a freight terminal, and *2T* is delivery with the involvement of two freight terminals. The combination of these variants of LC structures is a basic set of alternatives in the problem of justifying the optimal delivery variant.

The proposed methodology for evaluating the efficiency of the LC variants allows for considering the stochastic nature of the cargo delivery process by presenting the parameters of demand and technological indicators as random variables and takes into account the influence of the external environment on the LC effectiveness. It is necessary to simulate the technological processes of the shipment delivery to choose the best option for the LC structure to implement the described methodology. However, the proposed approach that is based on the evaluation of the areas of the most efficient use of the alternative LC structures allows for decision-makers to avoid simulation routines by choosing the best option for the given numeric characteristics of demand parameters.

Functional analysis of the demand parameters' influence on the efficiency of the LC showed that, for any of the considered LC structures, the total costs quadratically depend on the consignment weight and linearly—on the delivery distance and the request interval. The results of the assessment of the areas of the most efficient use of various LC structures suggest that the use of the simplest LC variant is optimal for a one-time delivery of small consignments by road transport, and the *2F*-variant should be used on road transport only in case it is not possible to arrange delivery without a partner forwarder.

As the directions of future research on the topic, the formation of the wider set of alternative LC structures and justification of the areas of their efficient use should be mentioned. The presented numeric results are case-sensitive and refer to freight deliveries by road transport between Ukraine and Poland, so additional experimental studies are needed to confirm obtained regularities.

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Appendix A

This section contains the methodology for calculation of the total expenses in the logistics chain.

Let us define costs of finding a customer E_{search}^{FF} as costs of the dispatcher's work during the searching procedures:

$$E_{search}^{FF} = s_h^{FF} \cdot t_{search} \cdot N_d^{FF}, \quad (A1)$$

where s_h^{FF} is unit costs for 1 h of the dispatcher's work (EUR/h);

t_{search} is time spent by a dispatcher while searching for a customer (h);

N_d^{FF} is the number of employed dispatchers.

Self-cost of the dispatcher's work can be determined based on the total monthly costs:

$$s_h^{FF} = \frac{1}{N_d^{FF} \cdot T_{month}} \cdot (E_{rent}^{FF} + E_{com}^{FF} + E_{cs}^{FF} + E_b^{FF} + E_d^{FF}) + \frac{E_{ds}^{FF}}{T_{month}}, \quad (A2)$$

where E_{rent}^{FF} is monthly office rental costs (EUR/month); E_{com}^{FF} is communal payments (EUR/month); E_{cs}^{FF} is expenses for communication services (payments for services of Internet providers, fixed and mobile telephony, services of specialized logistics portals) (EUR/month); E_b^{FF} is the costs of banking services (EUR/month); E_d^{FF} is depreciation for office equipment (EUR/month); E_{ds}^{FF} is the average salary of a dispatcher (EUR/month); T_{month} is the number of monthly hours of the forwarding enterprise operation (defined as the product of the average monthly number of working days and the average duration of a working day) (h/month).

The time to search for a client can be defined as the difference between the interval of the request receipt and the time spent on processing of the previous request:

$$t_{search} = I - t_{proc}, \quad (A3)$$

where I is the time interval between the moments of receipt of successive requests [h]; t_{proc} is duration of the received request processing (h).

Processing a request for delivery of a shipment consists of a number of operations:

- justification of the LC structure for servicing the received request for the consignment delivery;
- search for a carrier (carriers) and conclusion of relevant agreements;
- search for contractors for loading operations (if this type of work is not performed by other participants) and conclusion of contracts with them;
- registration of transport and customs documentation;
- search for a cargo terminal and conclusion of relevant contracts; and,
- search for a foreign partner forwarder and conclusion of relevant agreements.

The request servicing duration is defined as the sum of the duration for the operations that make up the servicing process, if these operations are performed by one dispatcher sequentially, i.e., for $N_d^{FF} = 1$:

$$t_{proc}^{N_d^{FF}=1} = t_{just} + t_{sC} + t_{sLU} + t_{doc} + t_{sFT} + t_{sFF}, \quad (A4)$$

where t_{just} is the time for justifying and selecting the LC structure [h]; t_{sC} is the time for searching for carriers and conclusion of contracts [h]; t_{sLU} is the time for searching for subcontractors in order to perform loading and unloading operations and the relevant contracts conclusion [h]; t_{doc} is the time for processing the customs and transport documentation associated with the shipment delivery (h); t_{sFT} is the time for searching for 3PL-provider and drawing up a contract (h); and, t_{sFF} is the time for searching for a partner forwarder and a contract conclusion (h).

If a forwarding company, when processing requests, uses the scheme of functional distribution of dispatchers' duties, the time of the request servicing is determined, as follows:

$$t_{proc} = t_{just} + \max_{i=1 \dots N_d^{FF}} t_{proc}^{(i)}, \quad (A5)$$

where $t_{proc}^{(i)}$ is the time for performing operations that are the duties of the i -th dispatcher [h].

The costs E_{doc}^{FF} of the forwarder for preparation of documents regarding the consignment delivery from consignor to consignee are determined similarly to (A1):

$$E_{doc}^{FF} = s_h^{FF} \cdot t_{doc}, \quad (A6)$$

The costs E_{just}^{FF} of justifying the LC structure and searching for contractors are determined on the basis of the cost of an hour of dispatchers and the duration of the relevant searching operations:

$$E_{just}^{FF} = s_h^{FF} \cdot (t_{just} + t_{sC} + t_{sFT} + t_{sFF}). \quad (A7)$$

The costs E_{LU}^{FF} for the organization and implementation of loading and unloading operations are determined by the formula

$$E_{LU}^{FF} = s_h^{FF} \cdot t_{sLU} + P_{LU}, \quad (A8)$$

where P_{LU} is the costs of contractors' services for the execution of the loading and unloading operations (EUR):

$$P_{LU} = Q \cdot \sum_{i=1}^{N_{LU}} T_{ti}^{LU}, \quad (A9)$$

Q is the consignment's weight (t); N_{LU} is the number of loading and unloading operations; T_{ti}^{LU} is the tariff of the i -th contractor (EUR/t).

The costs E_C^{FF} of carrier services are determined on the basis of the tariff per ton-kilometer:

$$E_C^{FF} = Q \cdot \sum_{i=1}^{N_C} L_i \cdot T_{tkm\ i}^C, \quad (A10)$$

where N_C is the number of carriers involved in the cargo delivery process; L_i is the shipping distance covered by the i -th carrier (km); and, $T_{tkm\ i}^C$ is the i -th carrier's tariff (EUR/tkm).

If the weighted average tariff for carrier services T_{tkm}^C is used, the value E_C^{FF} can be determined in the following way:

$$E_C^{FF} = Q \cdot L \cdot T_{tkm}^C, \quad (A11)$$

$$T_{tkm}^C = \frac{1}{L} \sum_{i=1}^{N_C} L_i \cdot T_{tkm\ i}^C, \quad (A12)$$

where L is the distance from consignor to consignee (km).

The costs E_{FT}^{FF} of freight terminal services are determined on the basis of tariffs for a consignment servicing:

$$E_{FT}^{FF} = Q \cdot \sum_{i=1}^{N_{FT}} \sum_{j=1}^{N_{ser}^{FT_i}} T_{ser\ j}^{FT_i}, \quad (A13)$$

where N_{FT} is the number of freight terminals involved in the delivery; $N_{ser}^{FT_i}$ is the number of types of services provided by the i -th terminal; and, $T_{ser\ j}^{FT_i}$ is the tariff for the j -th service of the i -th terminal (EUR/t).

The amount E_{cust}^{FF} of customs payments, made by a forwarder on behalf and at the expense of a freight owner, is determined based on the consignment value:

$$E_{cust}^{FF} = 0.01 \cdot Q \cdot c_t \cdot (\delta_{cust} + \delta_{imp}), \quad (A14)$$

where c_t is the value per 1 ton of goods (EUR/t); δ_{cust} and δ_{imp} are the rates of customs and import duties (%).

The costs E_{pack}^{FO} of forming a transport package include the cost of maintaining the means of packaging (pallets, containers), labor costs for personnel involved in the formation of transport packages, as well as the cost of packaging materials (packing tape, cellophane, etc.):

$$E_{pack}^{FO} = \frac{Q}{q_{cont}} \cdot [(t_{cont} \cdot s_h^{FO} + c_{pack} + k_{turn} \cdot c_{cont})], \quad (A15)$$

where q_{cont} is the nominal carrying capacity of the shipping container (t); t_{cont} is the time to form a transport package (h/unit); s_h^{FO} is cost of 1 h of work of an employee who forms transport packages (including the cost of work of special mechanisms, if such are used) (EUR/h); c_{pack} is the cost of

packaging materials (EUR/unit); c_{cont} is the cost of the shipping container (EUR/unit); and, k_{turn} is the coefficient that takes into account the turnover of shipping containers.

If a container is not returned to a shipper, then $k_{turn} = 1$; if the delivery contract provides for the container return, then k_{turn} is the reciprocal of the average number of revolutions of the shipping container prior to its write-off; if the cost of a container is included in the cost of goods for the consignee, then $k_{turn} = 0$.

The costs E_{FF}^{FO} of a freight owner to pay for the services of a freight forwarding company are the costs of contractor services paid by the freight forwarder on behalf of the freight owner, as well as the costs of directly paid for forwarding services:

$$E_{FF}^{FO} = P_{LU} + E_C^{FF} + E_{FT}^{FF} + E_{cust}^{FF} + P_{FF}, \quad (A16)$$

where P_{FF} is the cost of freight forwarding services (EUR):

$$P_{FF} = (E_{search}^{FF} + E_{doc}^{FF} + E_{just}^{FF} + E_{LU}^{FF} - P_{LU}) \cdot (1 + R_{FF}), \quad (A17)$$

R_{FF} is the profitability level of a freight forwarder.

The loss of the freight owner due to the capital immobilization E_{loss}^{FO} is estimated as follows:

$$E_{loss}^{FO} = \frac{Q \cdot c_t \cdot \alpha \cdot t_d}{365 \cdot 24 \cdot 100}, \quad (A18)$$

where t_d is the time of the consignment delivery (h); α is the coefficient considering losses due to freezing of funds while the delivery of a shipment (%/year).

A common practice is to estimate the value of the coefficient α as the average value of the annual deposit rate offered by banks in the shipper's region: losses due to the freezing of funds are estimated as possible incomes of the freight owner from placing funds constituting the value of the consignment on a bank deposit.

The costs E_{tr}^C of the carrier for operations on the consignment's movement are determined on the basis of the constant and variable components of costs:

$$E_{tr}^C = s_h^C \cdot t_{tr} + s_{km}^C \cdot L, \quad (A19)$$

where s_h^C and s_{km}^C are the constant and variable components of transportation costs, (EUR/h) and (EUR/km); and, t_{tr} is the travel time of the loaded vehicle (h).

Determining the travel time on the basis of the average technical speed of the vehicle, we obtain the following relationship:

$$E_{tr}^C = L \cdot \left(\frac{s_h^C}{V} + s_{km}^C \right), \quad (A20)$$

where V is the average vehicle speed during the delivery (km/h).

The costs E_{LU}^C of a carrier for the vehicle downtime during loading operations are determined on the basis of the constant component of costs for the vehicle use:

$$E_{LU}^C = s_h^C \cdot Q \cdot (t_t^L + t_t^U), \quad (A21)$$

where t_t^L and t_t^U are the duration of loading and unloading operations per 1 ton of cargo (h/t).

The costs E_{cust}^C for downtime at a customs point can be estimated similarly:

$$E_{cust}^C = s_h^C \cdot t_{cust}, \quad (A22)$$

where t_{cust} is the duration of downtime at a customs point (h).

The costs E_{LU}^{FT} for freight terminals associated with the consignment transshipment can be determined by the formula

$$E_{LU}^{FT} = s_{h(LU)}^{FT} \cdot Q \cdot (t_t^{TL} + t_t^{TU}), \quad (A23)$$

where $s_{h(LU)}^{FT}$ is the cost of 1 h of work on the shipment of goods (EUR/h); t_t^{TL} and t_t^{TU} are the duration of loading and unloading operations per 1 ton of cargo when the terminal facilities are used (h/t).

The costs E_{pack}^{FT} of a freight terminal associated with the disembodiment of received transport packages, as well as with the formation of consignments to be sent, are determined, as follows:

$$E_{pack}^{FT} = Q \cdot s_{h(pack)}^{FT} \cdot t_h^{pack}, \quad (A24)$$

where $s_{h(pack)}^{FT}$ is the cost of 1 h of work on the assembly and disassembly of a consignment (EUR/h); t_h^{pack} is the time for disassembling of a transport package and the formation of a new one per 1 ton of cargo (h/t).

The costs E_{store}^{FT} of the terminal for intermediate storage can be estimated on the basis of the cost of 1 h of storage of 1 ton of cargo:

$$E_{store}^{FT} = Q \cdot s_{th}^{FT} \cdot t_{store}, \quad (A25)$$

where s_{th}^{FT} is the cost of 1 h of storage of 1 ton of cargo (EUR/(t·h)); t_{store} is the time of intermediate storage of a consignment at the warehouse of a freight terminal (h).

Tax deductions for enterprises that are the LC elements are calculated for the main types of taxes—value-added tax and income tax.

The value-added tax amount is calculated on the basis of the corresponding rate:

$$VAT = \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot (IC - E_{paid}), \quad (A26)$$

where δ_{VAT} is the value added tax rate (%); IC is the income of an enterprise (EUR); E_{paid} is the cost of services and goods of third parties paid by the enterprise and included in its operating costs (EUR).

The income tax amount is determined based on the positive value of the company's net profit and income tax rate:

$$PT = 0.01 \cdot \delta_{PT} \cdot NP, \quad (A27)$$

where δ_{PT} is the income tax rate (%); NP is the net profit (EUR):

$$NP = IC - E_{total} - VAT + \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot E_{paid}, \quad (A28)$$

E_{total} is the total operating costs of an enterprise (EUR).

In accordance with the principles of mutual settlements between participants of the transport market, the freight forwarder's income is the amount paid by the freight owner as a reward for the forwarding services: $IC_{FF} = P_{FF}$. Revenues of terminals and carriers are the corresponding amounts paid to them as to contractors by the forwarder: $IC_{FT} = E_{FT}^{FF}$, $IC_C = E_C^{FF}$.

When delivering a consignment, a carrier pays fuel and lubricants costs, as well as the costs of maintenance and repair of vehicles, which already include the value-added tax. These cost items form the variable component of the cost of transportation; therefore, based on this indicator, the costs E_{paid}^C of third-party services paid by the carrier can be determined:

$$E_{paid}^C = s_{km}^C \cdot L. \quad (A29)$$

The costs of third-party services are included in the cost of 1 h of a forwarder work. These services include office rent expenses, costs of utilities and banking services, as well as communication services' costs. Thus, the cost component $s_{h(paid)}^{FF}$ can be calculated, as follows:

$$s_{h(paid)}^{FF} = \frac{1}{T_{month}} \cdot (E_{rent}^{FF} + E_{com}^{FF} + E_{cs}^{FF} + E_b^{FF}). \quad (A30)$$

Subsequently, the amount E_{paid}^{FF} paid by a forwarding company to third-party organizations can be calculated by the formula

$$E_{paid}^{FF} = s_{h(paid)}^{FF} \cdot I. \quad (A31)$$

Similarly, the costs of freight terminal services include the cost of purchased services and goods, which may include fuels and lubricants, utilities, communication services, etc. It can be argued that the share δ_{paid}^{FT} of these components in the self-cost value is constant, based on which the costs E_{paid}^{FT} of paid third-party organizations' services are determined, as follows:

$$E_{paid}^{FT} = Q \cdot \delta_{paid}^{FT} \cdot \left[s_{h(LU)}^{FT} \cdot (t_t^{TL} + t_t^{TU}) + s_{h(pack)}^{FT} \cdot t_h^{pack} + s_{th}^{FT} \cdot t_{store} \right]. \quad (A32)$$

The total operating costs E_{total}^{FF} of a freight forwarder include the cost of finding a client, justifying the LC structure and finding its participants, preparing customs and transport documentation, and organizing loading and unloading operations:

$$E_{total}^{FF} = E_{search}^{FF} + E_{just}^{FF} + E_{doc}^{FF} + E_{LU}^{FF} - P_{LU}. \quad (A33)$$

The operating costs E_{total}^{FT} of a terminal include the costs of the consignment transshipment, the formation and dismantling of transport packages, as well as the consignment intermediate storage:

$$E_{total}^{FT} = E_{LU}^{FT} + E_{pack}^{FT} + E_{store}^{FT}. \quad (A34)$$

Accordingly, for the carrier, the total operating costs include the costs of operations for the consignment movement, as well as for the downtime of vehicles during loading and unloading operations and at the customs point:

$$E_{total}^C = E_{tr}^C + E_{LU}^C + E_{cust}^C. \quad (A35)$$

Appendix B

This section presents the mathematical formulation of the shape of the total expenses as a functional dependence on the requests' flow parameters—the consignment volume Q , the delivery distance L , and the requests' time interval I .

Let us consider the functional dependence of the total expenses of the freight forwarder on the parameters of the requests flow.

Based on (A17), while taking dependencies (A1)–(A8) into account, the freight forwarder's income can be represented as

$$\begin{aligned} IC_{FF} &= s_h^{FF} \cdot (N_d^{FF} \cdot I - N_d^{FF} \cdot t_{proc} + t_{proc}) \cdot (1 + R_{FF}) = \\ &= I \cdot \left\{ N_d^{FF} \cdot s_h^{FF} \cdot (1 + R_{FF}) \right\} + \left\{ s_h^{FF} \cdot t_{proc} \cdot (1 + R_{FF}) \cdot (1 - N_d^{FF}) \right\}. \end{aligned} \quad (A36)$$

Afterwards, the value-added tax can be expressed in accordance with (A26) as follows:

$$\begin{aligned} VAT_{FF} &= I \cdot \left\{ \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot \left[N_d^{FF} \cdot s_h^{FF} \cdot (1 + R_{FF}) - s_{h(paid)}^{FF} \right] \right\} + \\ &+ \left\{ \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot s_h^{FF} \cdot t_{proc} \cdot (1 + R_{FF}) \cdot (1 - N_d^{FF}) \right\}. \end{aligned} \quad (A37)$$

Taking into account (A37) after transformations, we obtain the dependence of the net profit of a forwarder on the demand parameters:

$$NP_{FF} = I \cdot \left\{ \frac{1}{100 + \delta_{VAT}} \cdot \left[2 \cdot \delta_{VAT} \cdot s_{h(paid)}^{FF} - N_d^{FF} \cdot s_h^{FF} \cdot (\delta_{VAT} - 100 \cdot R_{FF}) \right] \right\} + \left\{ \frac{\delta_{VAT} - 100 \cdot R_{FF}}{100 + \delta_{VAT}} \cdot (N_d^{FF} - 1) \cdot s_h^{FF} \cdot t_{proc} \right\} \quad (A38)$$

Subsequently, the profit tax depends on the parameters of the demand for the services of a forwarder, as follows:

$$PT_{FF} = I \cdot \left\{ \frac{\delta_{PT}}{100 + \delta_{VAT}} \cdot \left[0.02 \cdot \delta_{VAT} \cdot s_{h(paid)}^{FF} - N_d^{FF} \cdot s_h^{FF} \cdot (0.01 \cdot \delta_{VAT} - R_{FF}) \right] \right\} + \left\{ \frac{0.01 \cdot \delta_{VAT} - R_{FF}}{100 + \delta_{VAT}} \cdot (N_d^{FF} - 1) \cdot \delta_{PT} \cdot s_h^{FF} \cdot t_{proc} \right\}. \quad (A39)$$

Based on the obtained dependencies, the total costs E_{Σ}^{FF} can be presented in this way:

$$E_{\Sigma}^{FF} = \left\{ s_h^{FF} \cdot t_{proc} \cdot (1 - N_d^{FF}) \right\} + I \cdot \left\{ s_h^{FF} \cdot N_d^{FF} \right\} + I \cdot \left\{ \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot \left[N_d^{FF} \cdot s_h^{FF} \cdot (1 + R_{FF}) - s_{h(paid)}^{FF} \right] \right\} + \left\{ \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot s_h^{FF} \cdot (1 + R_{FF}) \cdot t_{proc} \cdot (1 - N_d^{FF}) \right\} + I \cdot \left\{ \frac{\delta_{PT}}{100 + \delta_{VAT}} \cdot \left[0.02 \cdot \delta_{VAT} \cdot s_{h(paid)}^{FF} - N_d^{FF} \cdot s_h^{FF} \cdot (0.01 \cdot \delta_{VAT} - R_{FF}) \right] \right\} + \left\{ \frac{0.01 \cdot \delta_{VAT} - R_{FF}}{100 + \delta_{VAT}} \cdot (N_d^{FF} - 1) \cdot \delta_{PT} \cdot s_h^{FF} \cdot t_{proc} \right\}. \quad (A40)$$

As we can see, the total costs of a forwarder depend on the request interval and are not determined by the distance of delivery and the consignment weight. By grouping the factors for I and the remaining elements of the expression (A40), we obtain a linear relationship:

$$E_{\Sigma}^{FF} = a_0^{FF} + a_1^{FF} \cdot I, \quad (A41)$$

where $a_0^{FF} = \frac{s_h^{FF} \cdot t_{proc} \cdot (1 - N_d^{FF})}{100 + \delta_{VAT}} \cdot [100 + \delta_{VAT} \cdot (R_{FF} + 2) - \delta_{PT} \cdot (0.01 \cdot \delta_{VAT} - R_{FF})]$;

$$a_1^{FF} = s_h^{FF} \cdot N_d^{FF} + \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot \left[N_d^{FF} \cdot s_h^{FF} \cdot (1 + R_{FF}) - s_{h(paid)}^{FF} \right] + \frac{\delta_{PT}}{100 + \delta_{VAT}} \cdot \left[0.02 \cdot \delta_{VAT} \cdot s_{h(paid)}^{FF} - N_d^{FF} \cdot s_h^{FF} \cdot (0.01 \cdot \delta_{VAT} - R_{FF}) \right].$$

Let us study the functional dependency of the total costs of carriers from the parameters of the requests flow.

Given a tariff for 1 tkm, the amount of value added tax for a carrier is determined in accordance with (A26):

$$VAT_S = \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot (Q \cdot L \cdot T_{tkm}^C - s_{km}^C \cdot L). \quad (A42)$$

The net profit of a carrier based on the proposed dependencies can be defined in this way:

$$NP_S = Q \cdot L \cdot T_{tkm}^C - (E_{tr}^C + E_{LU}^C + E_{cust}^C) - \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot (Q \cdot L \cdot T_{tkm}^C - s_{km}^C \cdot L) + \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot s_{km}^C \cdot L. \quad (A43)$$

Based on (A43), the functional dependence of the income tax for a carrier on the parameters of the demand for transport services is determined, as follows:

$$PT_S = \frac{\delta_{PT}}{100} \cdot \left[\frac{Q \cdot L \cdot T_{tkm}^C - (E_{tr}^C + E_{LU}^C + E_{cust}^C) - \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot (Q \cdot L \cdot T_{tkm}^C - s_{km}^C \cdot L) + \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot s_{km}^C \cdot L}{100 + \delta_{VAT}} \cdot s_{km}^C \cdot L \right]. \quad (A44)$$

Thus, the dependence of the carrier's total costs E_{Σ}^C on demand parameters, taking into account (A42)–(A44), has the form

$$E_{\Sigma}^C = \left(1 - \frac{\delta_{PT}}{100}\right) \cdot \left[L \cdot \left(\frac{s_h^C}{V} + s_{km}^C \right) + s_h^C \cdot Q \cdot (t_t^L + t_t^U) + s_h^C \cdot t_{cust} \right] + \left(1 - \frac{\delta_{PT}}{100}\right) \cdot \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot (Q \cdot L \cdot T_{tkm}^C - s_{km}^C \cdot L) + \frac{\delta_{PT}}{100} \cdot \left[Q \cdot L \cdot T_{tkm}^C + \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot s_{km}^C \cdot L \right]. \quad (A45)$$

While transforming and simplifying the expression (A45), we obtain a linear functional dependence on the delivery distance and the consignment weight:

$$E_{\Sigma}^C = a_0^C + a_Q^C \cdot Q + a_L^C \cdot L + a_{QL}^C \cdot Q \cdot L, \quad (A46)$$

where $a_0^C = s_h^C \cdot t_{cust} \cdot \left(1 - \frac{\delta_{PT}}{100}\right)$;

$$a_Q^C = s_h^C \cdot (t_t^L + t_t^U) \cdot \left(1 - \frac{\delta_{PT}}{100}\right);$$

$$a_L^C = \left(1 - \frac{\delta_{PT}}{100}\right) \cdot \left(\frac{s_h^C}{V} + s_{km}^C \right) + \left(\frac{2 \cdot \delta_{PT}}{100} - 1 \right) \cdot \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot s_{km}^C;$$

$$a_{QL}^C = \left(1 - \frac{\delta_{PT}}{100}\right) \cdot \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot T_{tkm}^C + \frac{\delta_{PT}}{100} \cdot T_{tkm}^C.$$

Let us consider the total costs of cargo terminals as a function of the parameters of demand for freight forwarding services.

The amount of value added tax paid by the terminals depends on the parameters of the requests flow, as follows:

$$VAT_{FT} = Q \cdot \frac{\delta_{VAT}}{100 + \delta_{VAT}} \cdot \left\{ T_{ser}^{FT} - \delta_{paid}^{FT} \cdot s_{h(LU)}^{FT} \cdot (t_t^{TL} + t_t^{TU}) - \delta_{paid}^{FT} \cdot s_{h(pack)}^{FT} \cdot t_t^{pack} - \delta_{paid}^{FT} \cdot s_{th}^{FT} \cdot t_{store} \right\}. \quad (A47)$$

The net profit of the cargo terminal participating in the delivery of a shipment is defined as the following dependence on the parameters of the demand for freight forwarding services:

$$NP_{FT} = Q \cdot T_{ser}^{FT} \cdot \frac{100}{100 + \delta_{VAT}} + 2 \cdot E_{paid}^{FT} \cdot \frac{\delta_{VAT}}{100 + \delta_{VAT}} - E_{total}^{FT}. \quad (A48)$$

At the same time, the costs for third-party services E_{paid}^{FT} paid in the process of cargo owners servicing and the total operating costs E_{total}^{FT} of freight terminal depend on the demand parameters, as follows:

$$E_{paid}^{FT} = Q \cdot \delta_{paid}^{FT} \cdot \left[s_{h(LU)}^{FT} \cdot (t_t^{TL} + t_t^{TU}) + s_{h(pack)}^{FT} \cdot t_t^{pack} + s_{th}^{FT} \cdot t_{store} \right], \quad (A49)$$

$$E_{total}^{FT} = Q \cdot \left[s_{h(LU)}^{FT} \cdot (t_t^{TL} + t_t^{TU}) + s_{h(pack)}^{FT} \cdot t_t^{pack} + s_{th}^{FT} \cdot t_{store} \right]. \quad (A50)$$

Subsequently, the amount of income tax for a freight terminal can be represented as the following functional dependency:

$$PT_{FT} = Q \cdot \frac{\delta_{PT}}{100 + \delta_{VAT}} \cdot \left\{ T_{ser}^{FT} - \delta_{paid}^{FT} \cdot (1 - 0.01 \cdot \delta_{VAT}) \cdot \left[s_{h(LU)}^{FT} \cdot (t_t^{TL} + t_t^{TU}) + s_{h(pack)}^{FT} \cdot t_t^{pack} + s_{th}^{FT} \cdot t_{store} \right] \right\}. \quad (A51)$$

Taking the above dependencies into account, the total costs of a terminal are defined as the following linear dependence on the consignment weight:

$$E_{\Sigma}^{FT} = a_Q^{FT} \cdot Q, \quad (A52)$$

$$\text{where } a_Q^{FT} = \left[s_{h(LU)}^{FT} \cdot (t_t^{TL} + t_t^{TU}) + s_{h(pack)}^{FT} \cdot t_t^{pack} + s_{th}^{FT} \cdot t_{store} \right] \times \frac{100 + \delta_{VAT} - \delta_{paid}^{FT} \cdot \delta_{VAT} + \delta_{PT} \cdot \delta_{paid}^{FT} - 0.01 \cdot \delta_{VAT} \cdot \delta_{PT} \cdot \delta_{paid}^{FT}}{100 + \delta_{VAT}} + \frac{T_{ser}^{FT} \cdot (\delta_{VAT} + \delta_{PT})}{100 + \delta_{VAT}}.$$

Let us define the functional dependence of the total costs of a freight owner on the request parameters.

The costs of the freight owner for services of freight forwarders and contractors that are involved in the consignment delivery are determined on the basis of (A16):

$$E_{FF}^{FO} = Q \cdot [N_{LU} \cdot T_t^{LU} + N_{FT} \cdot T_{ser}^{FT} + 0.01 \cdot c_t \cdot (\delta_{cust} + \delta_{imp})] + Q \cdot L \cdot T_{tkm}^C + I \cdot [N_d^{FF} \cdot s_h^{FF} \cdot (1 + R_{FF})] + [s_{1h}^{FF} \cdot t_{proc} \cdot (1 + R_{FF}) \cdot (1 - N_d^{FF})], \quad (A53)$$

where N_{CP} is the number of customs points; N_{LU} is the number of loading operations performed by contractors; and, T_t^{LU} is the average tariff of contractors for loading operations (EUR/t).

While considering the delivery time as a function of demand parameters, we obtain a linear dependence of the following form:

$$t_d = Q \cdot (t_t^L + t_t^U) \cdot (1 + N_{FT}) + \frac{L}{V} + t_{cust}. \quad (A54)$$

Subsequently, the loss of a freight owner due to the freezing of funds constituting the consignment value, on the basis of (A18) and taking into account (A54), is defined as

$$E_{loss}^{FO} = \frac{Q \cdot c_t \cdot \alpha}{365 \cdot 24 \cdot 100} \cdot \left[Q \cdot (t_t^L + t_t^U) \cdot (1 + N_{FT}) + \frac{L}{V} + t_{cust} \right]. \quad (A55)$$

Selecting in the expression (A55) the numerical parameters of a request, we obtain the following relationship:

$$E_{loss}^{FO} = Q^2 \cdot \frac{c_t \cdot \alpha}{365 \cdot 24 \cdot 100} \cdot (t_t^L + t_t^U) \cdot (1 + N_{FT}) + Q \cdot L \cdot \frac{c_t \cdot \alpha}{365 \cdot 24 \cdot 100 \cdot V} + Q \cdot \frac{c_t \cdot \alpha \cdot t_{cust}}{365 \cdot 24 \cdot 100}. \quad (A56)$$

Based on (A15), while taking the above dependencies into account, the total costs of the freight owner are determined as a function of the following form:

$$E_{\Sigma}^{FO} = a_0^{FO} + a_{Q2}^{FO} \cdot Q^2 + a_{QL}^{FO} \cdot Q \cdot L + a_Q^{FO} \cdot Q + a_I^{FO} \cdot I, \quad (A57)$$

where $a_0^{FO} = s_h^{FF} \cdot t_{proc} \cdot (1 + R_{FF}) \cdot (1 - N_d^{FF})$;

$$a_{Q2}^{FO} = \frac{c_t \cdot \alpha}{365 \cdot 24 \cdot 100} \cdot (t_t^L + t_t^U) \cdot (1 + N_{FT});$$

$$a_{QL}^{FO} = \frac{c_t \cdot \alpha}{365 \cdot 24 \cdot 100 \cdot V} + T_{tkm}^C;$$

$$a_Q^{FO} = \frac{c_t \cdot \alpha \cdot t_{cust} \cdot N_{CP}}{365 \cdot 24 \cdot 100} + N_{LU} \cdot T_t^{LU} + N_{FT} \cdot T_{ser}^{FT} + 0.01 \cdot c_t \cdot (\delta_{cust} + \delta_{imp}) \cdot N_{CP} + \frac{1}{q_{cont}} \cdot (t_{cont} \cdot s_h^{FO} + c_{pack} + k_{turn} \cdot c_{cont});$$

$$a_I^{FO} = N_d^{FF} \cdot s_h^{FF} \cdot (1 + R_{FF}).$$

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