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Mathematical methods of finding optimal strategic decisions in developing regional freight transportation systems

Ph.D. Thesis summary

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The relevance of the research

As the country's economy develops, the cargo flows via particular regions of the country increase. At a certain point, the existing freight transportation infrastructure in these regions or even statewide may turn out to be insufficient to handle the increased cargo flows. In every country, modernizing existing transportation infrastructures, developing new elements in them, and building new such infrastructures are usually done in the framework of large-scale engineering projects. The implementation of these projects requires a large volume of investment, which federal and regional authorities cannot usually provide in full. If this is the case, forming certain partnerships with the private sector such as, for instance, public-private partnerships or signing concession agreements to implement the projects, may become an effective strategic decision that the authorities can make. (Here, it seems natural to assume that both legal and financial conditions that the authorities offer to their potential private partners are acceptable to the latter.) To start negotiations with the private sector on this matter, the authorities are to estimate a) the investment volume needed for a particular project, and b) the economic expediency of a project (how the project is expected to generate revenue in any particular planning period or in several such periods).

In developing/modernizing regional freight transportation infrastructures, building a new transport hub or a set of new transport hubs with access roads to them is one of the two critical parts of an engineering project that regional administrations may offer to their potential partners from the private sector to finance. Another essential element is associated with an effective management of this new or modernized transportation infrastructure in the competitive environment.

While the government of a country as a whole and/or the administration of a particular region of the country may recognize the importance of the project (associated with developing/modernizing the regional transportation infrastructure), all the efforts to make this project a reality may fail. That is, without securing the needed financing for the project, all the promises of the governments and regional administrations to the voters, particularly on developing/modernizing a local freight transportation infrastructure, may remain only promises. To avoid making unrealistic promises, as well as to make at least some of already made promises real, the governments/administrations need decision support tools. These tools should help them to a) estimate the expenses and the economic expediency associated with implementing the project, and b) negotiate with private investors both legal and financial conditions for their potential financial contributions. The latter is needed if the regional administration and the country's government cannot finance a particular project on developing/modernizing the local freight transportation infrastructure in full.

The thesis provides corresponding analytical instruments for developing such decision support tools. Particularly, a set of mathematical models and frameworks to determine the optimal modernization plan for a regional transport system, and to estimate the economic expediency of building a new transport hub in the particular competitive environment is proposed.

Statement of the problems under consideration

Two parts of a project on developing a regional freight transportation infrastructure — providing a set of construction and engineering works associated with building transport hubs and access roads to them and effectively managing these elements of the freight transportation infrastructure — are the subjects of consideration in the Chapter 1 of the thesis.

Whatever kinds of regional cargo transportation services are considered — between points within the region, between points in the other areas and locations in the region, and by transit via the region's territory — these advantages eventually allow one to provide faster and cheaper delivery of cargoes with the use of these services. Mathematical models, which can be used to estimate these advantages quantitatively and calculate transportation tariffs under which developing new cargo transport hubs in the region is economically expedient are proposed in the Chapter 2 of the thesis.

The objects of the research are problems of a) allocating transport hubs in a region, b) choosing the capacities and the schemes of moving cargo via these hubs, c) estimating the total expenses that are expected to be needed for all the construction and maintenance activities associated with these hubs, d) estimating the expected volume of the revenue that the functioning of these hubs may generate, and e) estimating the expediency of developing a cargo transport hub at a geographic point in a region.

The aim of the research is development of mathematical models underlying a decision support tools for estimating the needed volume of investment in developing a regional freight transportation infrastructure and estimating the expediency of developing a cargo transport hub at a geographic point in a region. This tools should allow a regional administration to start negotiations with potential investors from the private sector on financing the corresponding project. The proposed models should reflect the legal, engineering, and financial capabilities of the regional administration to offer to the private sector its cooperation in the framework of, for instance, a potential public-private partnership.

The goal of the research is to propose and study new mathematical models and frameworks that

(1) Capable to determine a) optimal (from the regional administration's viewpoint) locations of new cargo transport hubs in the region, b) total expenses associated with building both new transport hubs in the chosen (optimal) locations and access roads to them, c) the revenue

expected to be generated by the functioning of thus developed regional freight transportation infrastructure in any planning period being of interest to the regional administration, d) the competitiveness of the transshipment tariffs that the hub can offer, and e) the size of investment needed to build a new hub in the regional transport system and, thus, to estimate the economic expediency of developing this new cargo transport hub;

(2) Can be used as a basis for decision support tools that would be useful for a decision maker in making decisions on modernizing a region transport system in general and building new transport hubs in particular.

Researches relevant to the problem studied in the thesis

(Merakli and Yaman 2016, 2017) proposes a hub location model with a demand uncertainty described by systems of linear constraints. Similar to (Belenky 1981), they formulate a minimax optimization problem on two polyhedra and apply the dual transformation to linearize it and find the best solution in the worst-case of the demand combinations.

(Serper and Alumur 2016) considers the capacitated hub location model with different vehicle types and variable hub capacities. The model lets choose a) transportation modes (air, ground) and the vehicle type (airplane, trailer, truck) for both hub-to-hub and hub-to-node transportation, and b) the capacity level at a hub for each transportation mode.

An approach to modeling variable hub capacities is used in (Alumur et al., 2018), where the authors propose a framework for modeling congestions at hubs in hub location problems with a service time limit. (Alibeyg et al., 2016) introduces a class of hub network design problems with profit-oriented goal functions, which reflect the tradeoff between the profits obtained from moving the commodities and the costs of building transportation networks.

Among the most recent topics in location problems, there are those examining a variety of facility design aspects together with a particular location problem, for example, price, product range, and facility size aspects. Such model was considered in (Küçükaydin et al., 2011). In (Küçükaydin et al., 2011), the entrant aims to define the location and the attractiveness of each facility to be opened in the region proceeding from the existing facilities of the competitor. The competitor can react by adjusting the attractiveness of the facilities under the competitor's control. The objective of each player is to maximize its own profit, which depends on the player's market share. This market share is calculated via a gravity-based rule so that the share is proportional to the facility attractiveness and inversely proportional to the distance between the facility and a customer. The authors formulated the problem under consideration as a bilevel, mixed-integer, nonlinear programming problem. Using the Karush-Kuhn-Tucker optimality conditions, the authors converted this bi-level nonlinear programming problem into an equivalent one-level mixed-integer nonlinear programming problem.

Other researchers focus on pricing games as a part of the location problem. For example, (Fleckinger and Lafay, 2010) study a game where players chose their prices and their location at the same time. As a result, the authors prove that in their sequential game, the follower always earns more than the leader. Though the competition in location decisions has been studied in detail, the competition between the existing operator and a potential entrant into hub networks with origin-destination (OD) pairs has been studied much less. Perhaps, (Marianov et al., 1999) is the first article dedicated to this type of the competitive location problem in which the authors proposed the mathematical formulation for the follower's problem, where the existing transportation company operates in a hub-and-spoke network, and a new company wants to enter into the same market. In the proposed mathematical model, the customer preferences are modeled as follows: entrant captures a share of the flow of OD pair, depending on the difference between the entrant's and the existing operator's tariffs that are set for the customers. A problem similar to (Marianov et al., 1999) was considered in (Eiselt and Marianov, 2009), where the authors studied the follower's problem by applying it to the airport location problem. The major difference from the model proposed in (Marianov et al., 1999) is associated with the way of modeling preferences of the customers. That is, in (Eiselt and Marianov, 2009), the customer preferences are modeled with continuous gravity-like utility functions.

Thus, the review presented in the thesis shows that there are classes of problems with the formulations being close to the problems mentioned in Section I, which are under consideration in this chapter. These close problems have not been modeled and studied in a manner allowing one to use results from the reviewed publications for working out decisions by the parties negotiating a potential private-public partnership on developing a regional freight transportation infrastructure.

The scientific novelty of the study

The present thesis contributes to solving large-scale practical problems associated with making strategic management decisions on investing in the development or modernization of a regional freight transportation infrastructure. It introduces novel analytical tools for a) designing an optimal development or modernization plan for a local transport system, b) estimating the volume of investment needed to implement this plan, and c) assessing the possible future system performance in a competitive environment.

Chapter 1 of the thesis presents a new mathematical model for analyzing freight transport systems modernization and functioning in both a deterministic situation and under uncertainty by estimating the needed volume of investment in developing a regional freight transportation infrastructure. Two mathematical formulations of the corresponding problem a) with all the coefficients of the goal function being fixed, known real numbers, and b) with a least some of these coefficients being unlnown and considered as variables are presented there. The second

formulation is proposed in the form of a minimax problem with mixed variables and a linear structure of its system of constraints. The chapter contains the proof of a theorem that allows one to reduce this minimax problem to a mixed programming problem with the goal function and constraints having a linear structure.

Chapter 2 of the thesis presents a new mathematical model that allows one to formulate the problem of estimating the expediency of developing a cargo transport hub at a geographic point in a region as a nonlinear problem of finding the maximum of a minimax taken over a difference of two bilinear functions of four vector variables on polyhedral sets. A theorem proven in this chapter allows one to reduce finding a solution to this problem to solving a quadratic programming problem. Also, a new mathematical model for estimating the competitiveness of the transshipment tariffs that the hub can offer by finding the most unfavorable transportation tariffs for the hub under market conditions is proposed in this chapter. Using this model, the problem of finding the estimates of these tariffs is formulated as the problem of finding a minimax of a bilinear function with both vector arguments belonging to polyhedral sets, which is reducible (Belenky, 1981) to solving linear programming problems forming a dual pair. The possibility to reduce the considered problem to linear programming is important in large-scale systems, and transportation network systems are such large-scale ones. The solvability of the above-mentioned pair of linear programming becomes a sufficient condition of the transshipment tariff competitiveness. Establishing the transportation tariff competitiveness allows the regional administration to estimate the size of investment needed to build a new hub in the regional transport system and, thus, to estimate the economic expediency of developing this new cargo transport hub.

The main results obtained in the thesis

(1) New mathematical models to formalize problems associated with finding quantitative estimates of investments needed from the private sector for developing a regional freight transportation infrastructure;

(2) Three optimization problems are formulated on the basis of the proposed mathematical model. Two of these three problems allow one to find the estimates assuming that the information on the values of the parameters of the model is known exactly either for all the parameters or for a part of them. In both cases, the corresponding optimization problems are formulated as mixed programming ones. A robust optimization problem is formulated on the basis of the same mathematical model under uncertainty on the values of all the parameters of the model;

(3) Prove that the robust optimization problem is reducible to a mixed programming one with the system of constraints and the goal function having a linear structure under natural assumptions on the boundaries within which the values of the parameters can vary. Thus this assertion allows to solve a substantially nonlinear problem with mixed variables with the use of the

techniques for solving mixed programming problems with constraints and goal functions having a linear structure, which are implemented in the framework of standard software packages;

(4) A sufficient condition of the transshipment tariff competitiveness, and the framework for estimating whether to build a new cargo transport hub or to modernize the existing one at a particular geographic region;

(5) The methodology of finding: a) competitive tariffs for new transshipment services to offer to a set of potential clients, b) sufficient cargo volumes that will be profitable to move via the hub under the cost of providing the transshipment services there, and c) tariff values in the worst-case scenario.

The author's contribution includes that in the development and implementation of mathematical models and algorithms, proofs of the theorems, developing algorithms and their testing, collecting datasets, performing computational experiments, and preparing research papers.

The reliability and validity of the results obtained by the author is confirmed by numerical experiments and discussions in scientific groups. The research results were presented at leading international conferences and published in scientific journals.

The contribution to mathematical theory consists of a) proposed mathematical models for cargo transportation system functioning and modernization analysis, b) formulated and studied optimization problems, c) proved assertion to reduce the robust optimization problems to simpler solvable problems.

The practical applications of the proposed models is the possibility of their use in designing decision support tools for estimating a) the investment volume needed for developing or modernizing a regional freight transportation infrastructure, and b) the economic expediency of developing a new cargo transport hub. Also, the formulation of mathematical problems considered in Chapter 1 of the thesis, can be used in formalizing location-allocation problems in a wide range of industrial and transport systems, for instance, in optimally locating battery swapping stations.

Approbation of research results

The work underwent approbation at the following conferences:

(1) "Optimization models for estimating the volume of investment needed for developing regional infrastructures". XX April International Academic Conference On Economic and Social Development, Moscow, Russia, 2019.

(2) "Robust mathematical models associated with negotiating financial investments in large-scale transportation projects". 21st Conference of the International Federation of Operational Research Societies, IFORS-2017, Quebec City, Canada, 2017.

(3) “An example of the application of a robust approach to choosing an optimal regional freight transportation infrastructure”. 2017 International Transportation Economics Association Conference, Barcelona, Spain, 2017.

(4) “Mixed programming problems of optimally allocating and scheduling the openings of transport hubs and access roads to them in a geographic region”. 28th European Conference On Operational Research, Poznan, Poland, 2016.

The list of the published articles where the main scientific results of the thesis are reflected

The list of articles published in the journals included in international citation system Scopus:

(1) Fedin, G. An approach to estimating the economic expediency of developing a new cargo transport hub by a regional public administration/ Belenky, A., Fedin, G., Kornhauser, A., // International Journal of Public Administration (in press, has received favorable reviews, in press. 2020) (Scopus Q2)

(2) Fedin, G. Estimating the needed volume of investment in a public–private partnership to develop a regional energy/freight transportation infrastructure/ Belenky, A., Fedin, G., Kornhauser, A., // International journal of Public Administration. 2019. 42:15-16, 1275-1310 (doi.org/10.1080/01900692.2019.1652315) (Scopus Q2)

The list of articles published in the journals included in the HSE list “good journals”:

(1) Fedin, G. Modeling the interaction of parties of a public-private partnership for the design/development of regional freight transportation infrastructure/ Belenky, A., Fedin, G., Kornhauser, A. // Large-Scale Systems Control. 2019. 81. 50-89 (https://doi.org/10.25728/ubs.2019.81.3)

(2) Fedin, G., Applying the robust approach for the transport hubs with access roads location problem in the geographic region with existing transport system// Large-Scale Systems Control. 2018. 72. 108-137 (doi.org/10.25728/ubs.2018.72.5)

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