Fuzzy Knowledge Based System for Planning and Optimization of Tanker-Refueler Routes

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Abstract: *This paper deals with the mathematical formalization of tanker-refueller routing problem (T-RRP) under uncertain information about the demands of served ships. Several approaches are considered for increasing efficiency of T-RRP solving, in particular, synthesis of decision-making algorithms and mathematical models based on the interactive approach. The main focus of the paper deals with the application of fuzzy sets and fuzzy logic for modeling uncertain orders of served ships and for solving considered optimization problems for fuel transportation in uncertainty. The paper presents the developed fuzzy decision making system and simulation results for realization bunkering programs by solving T-RRP in different performance conditions.*

***Keywords*:** uncertain demand, fuzzy model, tanker-refueler, served ship, route optimization

1. INTRODUCTION

Fuzzy sets theory and fuzzy logic has been widely applied to the research and design practice [4, 5, 6, 32, 42, 44]. Its application is especially important and effective for control of objects with non-stationary functioning conditions as aircrafts, ships, underwater robots and others. Special attention should be paid to solving various transportation problems as problems in uncertain environment.

It is conventional to view transportation problem targeting minimization of the cost (goal) function concerning to the transportation of various kind of cargoes (oil, coal, fuel etc.) from several (or one) supplying ports (depots) to various receiving ports (nodes). It is very important to solve transportation problems taking into account the changeable character of functioning conditions of its environment. Intelligent technology, fuzzy systems and neuro-systems [6, 19, 21, 27, 32, 37, 44] can help to solve transportation problem in uncertainty efficiently.

2. PRIOR RESEARCH

Let’s consider prior models, decision-making algorithms, practical examples and modelling results dealing with the application of optimization methods to solving of different transportation tasks [23, 28, 34] . When assigning the transportation requests, dispatchers usually have built-in vague rules which can be used to assign a given amount of freight to be sent to a given distance for a given vehicle. Fuzzy systems with learning capabilities [37] can be trained to deal with complex processes like dispatcher. The application of fuzzy theory techniques for grouping of trips in the vehicle routing and scheduling problem is considered in [9], where composite similarity of the trip pair is computed by fuzzy integral. Based on the matrix of composite similarity, trip groups are identified by connecting trip pairs whose membership grade is greater than a given value. A definition of the optimal solution of the transportation problem with fuzzy cost coefficients as well as an multi-objective programming algorithm determining this solution are proposed in [1]. An algorithm, presented in [2], solves the transportation problem with fuzzy supply and demand values and the integrality condition imposed on solution. This algorithm is exact and computationally effective, although fuzzy supply and demand values can be fuzzy number of any type. The review of fuzzy sets theory applications in traffic and transportation, which parameters are clearly characterized by uncertainty, subjectivity, imprecision and ambiguity, is given in [33]. Fuzzy route choice model for traffic assignment is proposed in [7]. In [3] authors consider a fuzzy user-optimal route choice problem using a link-based fuzzy variation inequality formulation. Fuzzy approach for solving multi-objective transportation problem based on the fuzzy programming is considered in [24, 25]. The paper [38] presents a new methodology for safety analysis and synthesis based on fuzzy sets and evidential reasoning.

Many publications are devoted to optimization of various tasks in transport logistics [12, 16, 18, 20, 23, 28, 39].

From the first paper on fuzzy sets [43], published by Prof. Lotfi Zadeh, researchers received the theoretical foundation introducing fuzzy sets for successful solving of various problems in the conditions of uncertainty including transportation and routing problems [34, 39].

The main goal of this paper is to consider fuzzy models and fuzzy knowledge-based system for optimization of tanker-refueler routes in the conditions of capacity constraints and uncertain demands at nodes that practically presents a capacitive vehicle routing problem in fuzzy environment.

2. OPTIMISATION OF TANKER-REFUELER ROUTES AS CAPACITIVE VEHICLE ROUTING PROBLEM

One of the most important vehicle routing problems is routing problem for bunkering tankers or tanker-refuelers [35, 36, 40] that can be formulated as tanker-refueler routing problem (T-RRP). Such kind of tankers should provide bunkering (transportation and unloading) operations for various served (ordered) ships, which can be located in different marine ports and open sea points. Marine practice shows that very often the information about fuel demands of served ships and ports is uncertain. As usual ship's customer sends to bunkering company the order about quantity of fuel supplying as approximate value. It is possible to represent such kind of orders as fuzzy demands, for example, as fuzzy numbers with various shape of triangular membership functions [8, 14, 17]. Taking in to account the restricted fuel capacity of each tanker and fuzzy demands of ordered ships the T-RRP will transfer to capacitate tanker-refueler vehicle routing problem (CT-RRP) in uncertainty.

The efficiency of the preliminary bunkering operations planning can be evaluated by possibility to serve all ordered ships with maximum possible quantity of unloaded fuel and with minimum total length of tankers' routes. The vehicle routing problem with fuzzy demands at nodes

$$\tilde{q}_j = \left(\underline{q}_j, \hat{q}_j, \overline{q}_j\right) \tag{1}$$

is considered in [10, 35, 39, 41] , where $\hat{q}_j$ is a value of membership function of triangular fuzzy number $\tilde{q}_j$ with $\mu(\hat{q}_j) = 1$; $\underline{q}_j, \overline{q}_j$ are the lowest and highest possible values of uncertain demand, respectively, $\mu(\underline{q}_j) = 0$, $\mu(\overline{q}_j) = 0$.

Let's consider depot P_0 where bunkering company is located (Fig. 1) and propose fuzzy approach based on the application of relative signals for fuzzy system provided solving CT-RRP in uncertainty. The decision-maker from bunkering company needs to solve CT-RRP before the beginning of any bunkering operation [26]. At the deport P_0 bunkering company have *m* tankers for bunkering operations at the served marine region $(P_1...P_{12})$, where $L_{j,j+1}, \left(j \in \{0,1,2,...,11\}\right)$ is a distance (in miles) between j-th and $(j+1)$-th destinations. It is supposed that warehouse P_0 has satisfied quantity of fuel for any real set of demands of *n* ships which need fuel supplying for their further performance and mission continuation. Each *i*-th tanker (*i* = 1,.., *m*) has the varies fuel capacity Q_i , the served ships have various capacities S_j and various demands, q_j $(j = 1,...,n)$, respectively. The decision-making about including considered port P_{j+1} to current route will be informed through the application of developed fuzzy knowledge-based system based on the condition [22, 35]

$$\lambda_{j+1} \geq \lambda^*, \tag{2}$$

where λ^* is a preference value; λ_{j+1} is a current value of satisfaction level. Such satisfaction level λ_{j+1} can be calculated at each served port $\left(P_j\right)$ as possible level for next serving port $\left(P_{j+1}\right)$ with its fuzzy demand q_{j+1} .

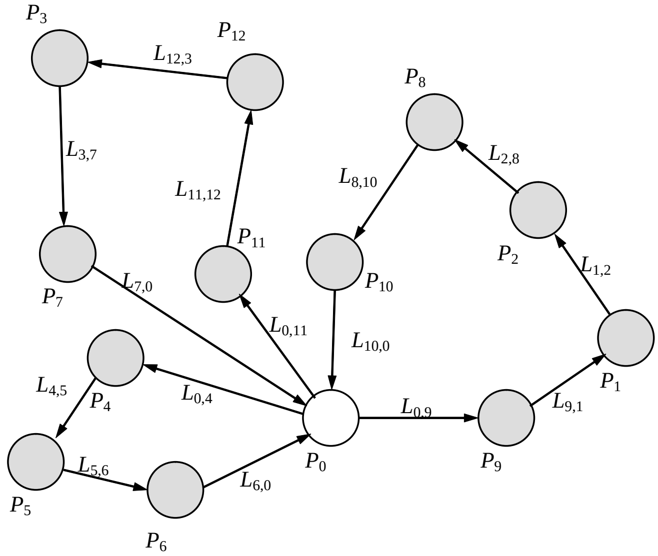

Fig.1 - CVRP with Fuzzy Demands of Served Ships

The developed decision-making algorithm based on the fuzzy logic [10] can be presented in the following way:

$$\lambda_{j+1} = FKBS\left[FRB\left(\underset{\sim}{x}_1, \underset{\sim}{x}_2, x_3\right)\right] . \tag{3}$$

In (3) we used next notations: FKBS is a fuzzy knowledge–based system; FRB is a fuzzy rule base with followed structure of fuzzy rules, for example, "**IF** (input signal $\underset{\sim}{x}_1$ is *Low*) **AND** (input signal $\underset{\sim}{x}_2$ is *Middle*) **AND** (input signal x_3 is *High*) **THEN** (output signal λ_j is *High*)"; λ_{j+1} is a value of satisfaction level for each alternative decision-making; $\underset{\sim}{x}_1 = \tilde{q}_{j+1} / \Delta\tilde{Q}_i$ is relative unit between fuzzy demands of the next $(j+1)$-th port $\tilde{q}_{j+1}$ and fuzzy value of the remaining tanker cargo $\Delta\tilde{Q}_i$; $x_2 = \Delta\tilde{Q}_i / Q_i$ – relative unit between fuzzy numbers $\Delta\tilde{Q}_i$ and tanker capacity Q_i; $x_3 = L_1 / L_2$ is relative unit between length L_1 and L_2 of two alternative routes R_1 and R_2 (R_1 is the route with 1st level of search of the next route candidate port and R_2 is the route of the 2nd level of search; $\Delta\tilde{Q}_i = \left(Q_i - \sum_{j=1}^{k}\overline{q}_j,\, Q_i - \sum_{j=1}^{k}\hat{q}_j,\, Q_i - \sum_{j=1}^{k}\underline{q}_j\right)$ is a fuzzy value of the remaining tanker cargo, where *k* is a number of served ships on the *i*-th route before current decision-making process; $\{Low, Middle, High\}$ is a set of the corresponding linguistic terms for input $\underset{\sim}{x}_1, \underset{\sim}{x}_2, x_3$ and output λ_{j+1} signals.

The characterized surface

$$Surf\left(x_1, x_3\right), x_2 = const ,$$

of fuzzy rule base FRB (3) for fixed input signal $x_2 = Middle$ is presented in Fig. 2.

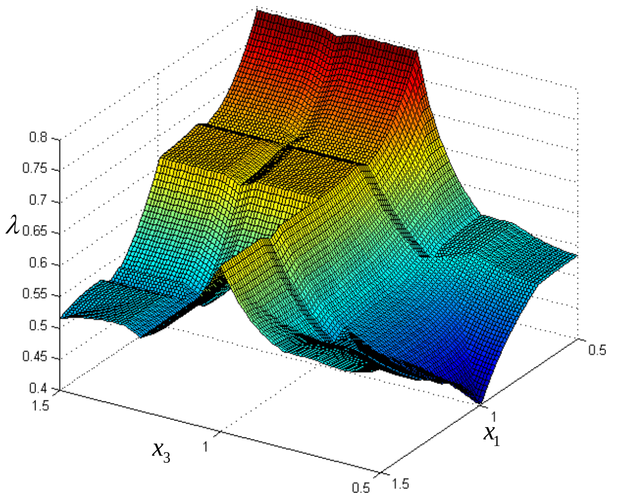

Fig. 2 - Characteristic surface of fuzzy knowledge-based system (3) with the fixed value of input signal x_2

The main criteria E_{BP} for evaluation of bunkering process efficiency based on solving CT-RRP with capacity constraints and fuzzy demands (1) of served ships can be presented as

$$\text{MAX}\, E_{BP} = \frac{1}{r}\sum_{i=1}^{r}\left(1-\frac{\Delta Q_i^{remain}}{Q_i}\right). \quad (4)$$

The criteria (4) can be transformed to the multi-objective form:

$$\Delta Q_i^{remain} \rightarrow \text{MIN},\ \left(i = 1,2,\ldots,r\right), \quad (5)$$

$$r \rightarrow \text{MIN}, \quad (6)$$

where ΔQ_i^{remain} is a remaining fuel capacity before tanker returning to depot P_0; r – number of routes.

3. FUZZY MODELS OF UNCERTAIN DEMANDS

The efficiency of the whole process of planning routes depends strongly on the efficiency of fuzzy decision support system. Therefore, it appears reasonable to apply simulation, learning and testing methods for fuzzy decision support system development. To evaluate the effectiveness of the fuzzy decision support system, it is necessary to form fuzzy models of bunkering operations using stochastic simulation models of fuzzy and crisp (real) fuel demands in the nodes.

A number of fuzzy-stochastic models are developed by authors for efficiency evaluation and selection of the best algorithms for planning and optimization of tanker-refueler routes under uncertainty in solving problems of the class CT-RRP with fuzzy demands (1). These models allow exploring the planning and implementation of the routes with different intensity of external disturbances and several sources of uncertainty for a priori information [26].

Let's consider in more details the proposed approaches for synthesis of fuzzy-stochastic models for planning routes and CT-RRP optimization in marine bunkering processes.

Simulation models of fuzzy demands (Fig. 3) will be formed in the style [8, 14, 17, 45] of fuzzy sets with triangular membership function (MF). In this case fuzzy demands $\tilde{q}_j = (\underline{q}_j, \hat{q}_j, \bar{q}_j)$ as MF's parameters for different ports can be determined by stochastic models (7)-(9):

$$\hat{q}_j = \nu_{3j-1} Q\ , \quad (7)$$

$$\underline{q}_j = \nu_{3j-2}\nu_{3j-1} Q\,, \quad (8)$$

$$\bar{q}_j = \left[\nu_{3j-1} + \left(1-\nu_{3j-1}\right)\nu_{3j}\right] Q\,, \quad (9)$$

where ν_{3j-2}, ν_{3j-1}, ν_{3j} are random variables with respective distribution law, $\nu \in [0,1]$; Q is a capacity of the tanker; and j is a number of port-applicant with fuzzy-uncertain demand $\tilde{q}_j$.

A more flexible simulation model for determining the parameters of fuzzy demands can be synthesized based on the following approach (10)-(12):

$$\underline{q}_j = A_j\left(1-\nu_{3j-2}\right), \quad (10)$$

$$\bar{q}_j = A_j\left(1+\nu_{3j}\right), \quad (11)$$

$$\hat{q}_j = A_j\left[\left(1-\nu_{3j-2}\right)\left(1-\nu_{3j-1}\right)+\left(1+\nu_{3j}\right)\nu_{3j-1}\right], \quad (12)$$

where $\nu_{3j-2} \in [0,1]$, $\nu_{3j} \in [0,1]$, $\nu_{3j-1} \in [0,1]$ are random variables automatically generated by the corresponding computer software generator of random values; $A_j, (j = 1\ldots N)$ is a constant for using the same type of tankers $Q_i = Q, (i = 1\ldots r)$ and the absence of a priori information about the types of vessels of customers.

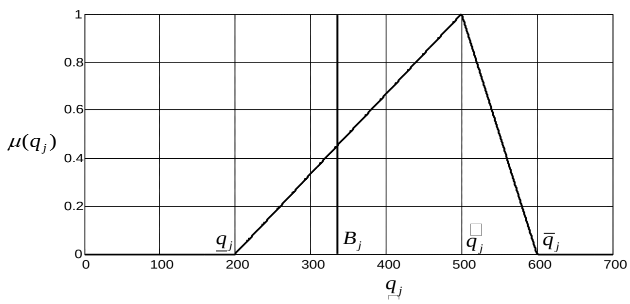

Fig. 3 - Models for fuzzy $\tilde{q}_j$ and crisp (real) B_j demands

For CT-RRP with heterogeneous tanker-refueler fleet $Q_i \neq Q_k, (i,k = 1\ldots r)$ the parameter A_j can be find as

$$A_j \leq \left[Q_{i\min} + (Q_{i\max} - Q_{i\min})/2\right]/2\,, \quad (13)$$

where $Q_{i\min}$, $Q_{i\max}$ are the minimum and maximum values of tanker's capacity from the set of heterogeneous tanker fleet;

$j = 1\ldots N; i = 1\ldots r$.

The stochastic approach that characterizes the non-stationary nature of the external disturbances for the bunkering processes can be used for the implementation of the simulation models of real demands in the following way:

$$B_j = A_j\left[\nu^k_{3j-2} + \left(1-\nu^k_{3j-2}\right)b^k_j\right], \left(j = 1...N\right), \quad (14)$$

where b^k_j is a random value, $b^k_j \in \left[0,1\right]$.

4. SIMULATION OF DECISION-MAKING PROCESS BASED ON FUZZY DEMANDS

During the decision-making process the suggested decision knowledge-based system compares satisfaction (preference) value λ^* and current satisfaction level value λ_{j+1} calculated at each served port (P_j) as a possible level for next serving port (P_{j+1}) taking into account its fuzzy demand $\tilde{q}_{j+1} = \left(\underline{q}_{j+1}, \hat{q}_{j+1}, \overline{q}_{j+1}\right)$. Average value of critical parameter (desired satisfaction level or preference level) is determined as $\lambda^* = 0.5$ based on the 2.48 $*10^6$ fuzzy-stochastic models of fuzzy and real demands in CVRP with 32 ports for 8 different marine bunkering programs and homogenous fleet of tankers. One example of the CT-RRP solving with 5 routes

$$\left\{R_1, R_2, R_3, R_4, R_5, R_6\right\}$$

is presented in Fig. 4. So, 5 tanker-refuelers (Fig. 4) should supply the corresponding fuel to 35 serving ships with different destination points of the sea.

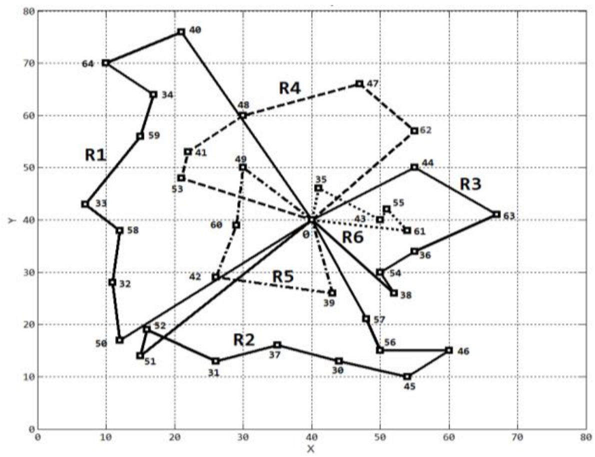

Fig. 4 – Modeling results for solution of the CVRP with fuzzy demands

Statistical data based on simulation results for CT-RRP with fuzzy demands $\tilde{q}_j = \left(\underline{q}_j, \hat{q}_j, \overline{q}_j\right)$ in 32 nodes and 2.48 $*10^6$ stochastic models of real demands are presented in Fig. 5. FKBS (2) has the preference value of $\lambda^* = 0.5$. Fig. 5a illustrates simulation results for 1st search level $\left(E_{BP}{}^{av} = 0.7836\right)$ when we consider only one next port-applicant for fuel supplying. Fig. 5b illustrates simulation results for the 2nd search level $\left(E_{BP}{}^{av} = 0.8370\right)$ when we consider two next sequenced port-applicants for fuel supplying. Modelling results (Fig. 5) confirm the effectiveness of suggested structure of the fuzzy knowledge-based system (2) for solving CT-RRP [10, 22, 23, 36, 41], as well as high information level of relative input data and substantial influence of the preference value λ^* to the current decision-making process.

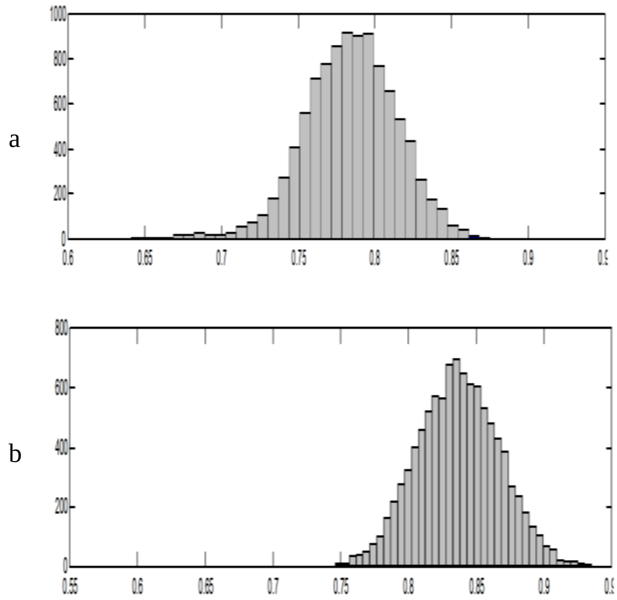

Fig. 5 - Distributions of E_{BP} value for CVRP: simulation results

Special investigations (Fig. 6) confirm that satisfaction value $\lambda^* = 0.5$ is most rational value for solving CVRP with fuzzy demands. Fig. 6 presents the averaged simulation results for 8 bunkering programs, in particular, such dependences as

$$L^{av}{}_{add} = f\left(\lambda\right), \; L^{av}{}_{plan} = f\left(\lambda\right), \; L^{av}{}_{total} = f\left(\lambda\right),$$

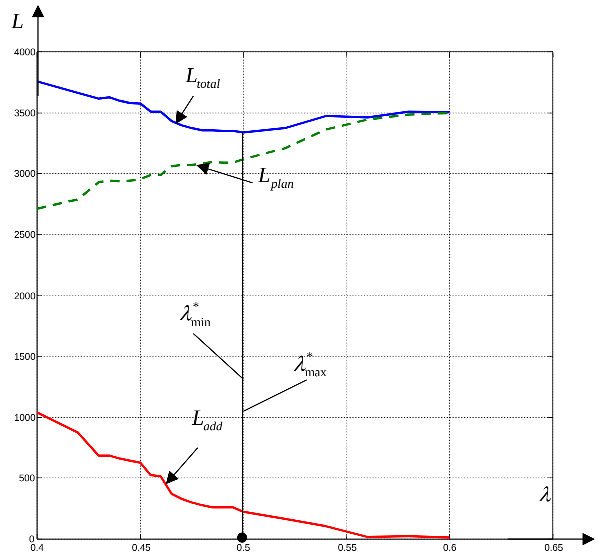

Fig. 6. Averaged simulation results of 8 bunkering programs implementation for determination of preference value λ^*

where λ is a satisfaction value; $L^{av}{}_{plan}$ is an average planning length of all routes; $L^{av}{}_{add}$ is an average additional length of all additional routes realized when the last fuzzy demands on the planning routes could not serve; $L^{av}{}_{total}$ is an average total length of planning and additional routes

$$L^{av}{}_{total} = L^{av}{}_{plan} + L^{av}{}_{add} .$$

In this case the rational preference value λ^* can be determined as

$$\lambda^* = Arg \underset{i}{Min} L^{av}{}_{total}(\lambda_i), (i = 1...n), \lambda_i \in [0,1] .$$

5. CONCLUSION

The proposed fuzzy models and fuzzy knowledge-based system allows solving CT-RRP in fuzzy conditions given the uncertainty of the demand data at nodes. The simulation and modelling results for realization of different bunkering programs by tanker-refueler fleet confirm efficiency of the developed algorithms and models for optimization of the fuel transportation process, in particular, for optimization of the planning tanker-refueler routes taking into account fuzzy conditions of the sea environment and fuzzy demands of the serving ships. For future research we plan to use various efficient methods [11, 13, 15, 29, 30, 31] of structural-parametric optimization for increasing efficiency of the developed fuzzy models and fuzzy knowledge-based system.

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