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APPLICATION OF FUZZY CELLULAR AUTOMATA TO OPTIMIZE A VESSEL ROUTE CONSIDERING THE FORECASTED HYDROMETEOROLOGICAL CONDITIONS

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The object of research is the processes of planning the minimum operating costs of a vessel with minimal risk to it and its cargo, considering the forecasted hydrometeorological conditions. The aim is to increase the fuel efficiency of a vessel's passage, considering the forecast of weather conditions when forming an optimal safe route in the e-Navigation system. To achieve the research goal, conventional cellular automata and the mathematical apparatus of fuzzy sets and fuzzy logic were used in the process of decision-making and assessment of the impact of weather conditions on traffic efficiency. The devised approach makes it possible to synthesize an optimal route for the vessel, which ensures minimum fuel consumption and has minimal risk for the vessel and cargo while considering variable hydrometeorological conditions along the route. Minimization of operating costs is achieved through the ability of cellular automata to describe the complex behavior of objects, considering local rules. Automata are a computing system in discrete spaces. Data uncertainty has led to the need to use a fuzzy system, the effectiveness of which depends on the quality and accuracy of rules. Fuzzy automata, by combining fuzzy logic and automata theory, made it possible to process continuous steps and model the inherent uncertainty. To determine the state of cells of a fuzzy cellular automaton and the transition function between them, a system of productive rules and membership functions was used. It is the consistency of the system of productive rules when using fuzzy logic to build a cellular automaton that enables the construction of a quasi-global optimal routing method in comparison with conventional methods for calculating the ship's route

Keywords: e-Voyage, navigation situation, route, cellular automaton, fuzzy logic, weather conditions

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1. Introduction

With the development of maritime transport and the increase in the level of sea transportation, more and more attention is paid to the selection of energy-efficient transit routes in the shipping industry. This is due to the fact that shipping consumes about 5 % of the world's oil production, which is approximately 4–5 million barrels of oil per day [1]. Therefore, devising approaches to optimize navigation to reduce fuel consumption is an urgent need in the development of systems for planning and controlling the movement of ships in various areas of their application. Most mathematical statements of optimization problems and methods for solving them are very complex from a computational point of view. Therefore, over the decades, a slow transition from very simplified forms to increasingly complex ones has been carried out. And only the explosive growth of computing power made it possible to move on to solving very complex models. At the same time, even models operating under a mode close to real time are considered.

However, this period is characterized not only by the growth of computing power but also by the presence of a significantly larger (by orders of magnitude) amount of weather data and forecasts, which will inevitably lead to increased interest in meteorological ship routing.

A range of possible solutions is offered to significantly reduce fuel consumption during sea transportation. It may be a difficult matter to choose among the many desired projects related to liner shipping. And there may be simpler options that involve the calculation of the best sailing speed taking into account currents, ice conditions, temperature, and other weather factors in a specific voyage.

Under favorable weather conditions, within the limits imposed by sea routes, the optimal route is calculated as a loxodrome (or orthodrome), in which fuel consumption is minimal. With this approach, tabular values of the influence of external factors and parameters of the ship on the characteristics of the ship's movement are used. The main issue is that when the hydrometeorological conditions in the sailing area deteriorate, the complexity and influence of the navigational situation on the movement of the vessel is unknown a priori. And when sailing under difficult hydrometeorological conditions, it is necessary to observe safety criteria that protect the integrity of the vessel and its cargo. Therefore, research into searching for new solutions to the problem of dynamic optimization of the ship's speed and course for real-time mode, taking into account hydrometeorological conditions, is relevant.

2. Literature review and problem statement

Work [2] gives an overview of studies on the formation of a safe optimal route for the passage of ships, taking into account the forecast of weather conditions, explaining the main methodological approaches and key disciplines that deal with this problem. Traditionally, to solve a multi-objective optimization problem with static and dynamic constraints and a large set of decision variables (including the coordinates of successive route points) taking into account weather conditions, methods of isochrones, dynamic programming, calculus of variations, path-finding algorithms and heuristics, methods of artificial intelligence and machine learning are used. However, most of these methods and their combinations do not take into account the uncertain nature of weather forecasts, which is explained by the complexity of such a description. Thus, a method is needed to effectively deal with these challenges and constraints, such as cellular automata.

Paper [3] provides a method of routing ships taking into account meteorological conditions, which is able to formalize the uncertainties of weather forecasts during route optimization. This method uses the w-MOEA/D algorithm, which involves modeling the decision maker using the w-dominance relation. But the paper does not consider the quantitative characteristics of the influence of the human factor on fuel consumption. In addition, due to computational complexity, this algorithm does not function on a real time scale and is focused only on part of the target space.

The simultaneous optimization of the ship's course and speed for the entire transit route within the estimated time of arrival, for safe and energy-efficient navigation, is considered in [4]. The authors propose to build a dynamic model of the sea space with sets of hydrometeorological data extracted from records of previous voyages, which, based on two artificial neural network models, predict the rate of fuel consumption and engine operation mode. But the study did not consider the procedure for applying the results for their implementation under the real-time mode of ship's operation. In addition, the results are not accurate due to the failure to take into account in the model such hydrometeorological factors as, for example, currents, ice-covered waters, etc.

Work [5] presents the concept of a probabilistic road map for laying a route, which allows solving the task of taking weather conditions into account. Using the concept of a probabilistic road map, a study of possible ways of bypassing dangerous zones is carried out. Taking into account the digital map of the ship's navigation area, as well as weather forecast data, a modified algorithm of the probabilistic road map for constructing the ship's route is presented. And although the proposed algorithm works in real time, determining the best solution in less than 1 minute, the lack of reliable statistical weather data significantly affects the accuracy of route construction. It is possible to improve data about weather conditions (wind, waves, sea currents) by using fuzzy sets.

The software, developed taking into account CMEMS (Copernicus Marine Environment Monitoring Service) wave forecasting systems and available for free use, is considered in [6]. In it, the authors describe the implementation of SIM-ROUTE complex software for ship routing, based on the A* route determination algorithm. This algorithm is used to optimize the sailing route. The goal of the software is to provide a comprehensive, open, and lightweight tool, including pre- and post-processing, for ship route simulation. A limitation of the study is the consideration of only the influence of waves. But an equally serious problem for ships is the wind situation, wave resistance of the ship, and the influence of water currents on navigation along the route. In addition, the program is aimed at achieving only one of the goals of meteorological ship routing – minimization of navigation time, and fuel consumption and atmospheric emissions are an additional goal. In addition, the path construction algorithm used constantly seeks a compromise between accuracy, user-friendliness, and computation time, assuming standard computing resources.

In [7], an improved algorithm of ant colonies (IMACO) is proposed based on the method of order preference by similarity to the ideal solution (TOPSIS). It is able to take into account the risks of ship navigation and the cost of fuel consumption under difficult hydrometeorological conditions. The IMACO method simulates the navigational environment and calculates fuel consumption taking into account navigational risks for the vessel. Compared to the optimization algorithm of the ant colony with a single object (SACO), the method proposed by the authors makes it possible to comprehensively solve the problem of choosing the route strategy of the ship. However, the algorithm of pheromone evaporation is not described in the paper, which in some way reduces the accuracy of the results. In addition, different shipping companies use the developed algorithm to obtain different route planning grid maps according to differences in navigation strategies. That is, shipping companies can more easily choose routes that suit their own navigation strategies. But due to the different strictness of the requirements for navigation management of different companies, different routes are chosen simultaneously in the same area of the sea. That is, due to different requirements, there is no unambiguous statement and solution of the optimization problem.

The study of a new decision support system for route optimization, which is aimed at detecting excessive maneuvers and accelerations caused by adverse hydrometeorological conditions at the current time and in the current location, is reported in [8]. Unfortunately, the paper does not contain a device for checking the inconsistency of knowledge in a decision support system. In addition, the implemented on-board decision support system (DSS) implements a marine weather route optimization algorithm to prevent cargo loss based only on historical AIS trajectories. DSS detects excessive movements and accelerations caused by bad weather at a certain time and place based on the appropriate threshold values of adverse weather conditions. But the paper does not use weighted thresholds for adverse weather conditions, which does not allow for the formation of adaptive route optimization schemes, since different weather thresholds (wind speed and wave direction) are taken into account separately when planning an alternative route. Also, the proposed approach allows taking into account a number of other factors, such as vessel-specific variables (size, deadweight, displacement, etc.), as well as real-time performance characteristics (speed, power, heading, etc.) obtained from on-board sensors.

In study [9], an algorithm for determining vessel movement routes is proposed, based on the three-dimensional modified isochron method, and it uses a recursive direct technique and a floating grid system for vessel tracks. The work does not confirm that the obtained solution is optimal. In the proposed method, multi-dynamic elements are used as weighting factors in the objective functions to optimize the results. But the method has two significant drawbacks. Firstly, there is no procedure for calculating the weighting coefficients and, secondly, it is impossible to use it for real-time work.

Paper [10] proposed a framework that uses various data sources, including ship design, weather forecast, and historical sailing information, to calculate fuel consumption under the influence of navigational conditions. Improvements to the classical A* algorithm, including directed search and three-dimensional expansion, are proposed to improve routing efficiency. But it has not been proven what the minimum amount of information, especially meteorological information, must be processed to calculate fuel consumption. The proposed algorithm does not take into account such parameters as speed regulation of the main engine and propeller drive motors, which cannot be achieved under an ideal mode, local properties of wind, waves, ship movement and rudders, which reduces the accuracy of routing. In addition, the current method does not take into account the more detailed information from electronic nautical charts and weather forecasts, as well as the more realistic requirements of ship captains.

Study [11] considered the advantages of optimizing the route of ships taking into account hydrometeorological conditions according to the received estimates of ship emissions for minimum distances. However, the work does not contain data on distances significantly different from the minimum. The work combines the assessment of pollutants from shipping and their mitigation through weather route optimization. Moreover, this is one of the rare studies in which two areas of research are indicated, which are usually analyzed separately, but discussed together. The developed open-source ship weather routing software uses only high-resolution wave forecasting to obtain an optimized route in terms of sailing time. Other weather factors are not taken into account.

In paper [12], based on a large amount of information about the weather forecast and known technical characteristics of the vessel, weather routing is defined as follows. This is the process of making a decision on finding the optimal route in terms of the expected time of passage of waypoints and arrival at the final point of travel or engine power when performing a certain voyage, taking into account the expected weather and sea conditions. The authors propose to consider the task of determining the passage of a ship from one port to another with unstable weather and sea conditions. Then the problem of routing ships under weather conditions differs from the conventional task of a traveling salesman. It should be considered as a combined routing problem, where the weather information is different on each section of the route. However, the procedure for selecting sections of the route when weather conditions change has not been determined. Although the paper discusses the demarcation of planning levels in the construction of optimal routes and asserts the interaction between them and the necessity of long-term decisions for lower-level decisions, the models do not contain a significant amount of detail (hydro-meteorological conditions) for the implementation of optimization decision support systems for marine applications. Another still unsolved problem is the impossibility of applying the proposed approach for online work.

In a number of studies, the minimization of risk when drawing up routes taking into account the weather has been investigated. In [13], wind is identified as the main safety threat during a voyage, and researchers aim to minimize the time a ship spends in areas of strong wind. But minimizing the risk can cause an increase in the total time, which requires as an alternative to plan the ship's route according to the weather. The proposed methods do not make it possible to simultaneously achieve a reduction in travel time, fuel consumption, and the risk factor. In addition, the given multi-criteria evolutionary algorithm of weather routing can be applied only to a model of a vessel with a hybrid power plant. And although the execution time of the algorithms seems acceptable for dynamically updating routes, the resulting route is often suboptimal.

Paper [14] examines sailing conditions (height and length of waves, wind), which pose a safety risk, depending on the specifics of the voyage. The model achieves minimization of fuel consumption, taking into account adverse weather conditions in the sailing area and not taking into account the time characteristics of the process.

Adverse weather conditions can lead to human casualties in all types of shipping, especially when carrying out cargo operations [15]. Arctic shipping routes can significantly reduce fuel consumption compared to other routes, but they are very sensitive to weather conditions. And although the paper carefully describes the factors that affect commercial shipping in the Arctic region, classified threats to the environment, but there is no statement and solution of the optimization problem. In addition, materials are not provided on how the changing ice conditions on the route of movement can affect its rapid enumeration.

In order to minimize fuel consumption under ideal weather conditions, they try to keep the ship's speed constant throughout the voyage. But the influence of weather conditions requires the ship to slow down during bad weather and speed up during calm periods. Therefore, the use of the concept of virtual arrival is suggested to ship owners in order to save fuel [16]. The cited paper empirically estimates the potential reduction in fuel consumption and emissions from the implementation of a virtual arrival policy in a global context based on vessel location data from the Automated Identification System (AIS). A significant shortcoming of the work is the emphasis on fuel cost savings and emissions only from the widespread implementation of virtual arrival compared to the existing policy of mooring in the order of the queue and the standard sailing charter period with «maximum dispatch».

The decrease in the average speed of movement along the route is not supported by data on taking into account the weather and sea conditions of sailing.

It is clear that the increased interest in meteorological ship routing has not yet resulted in a definitive solution to the problems facing the industry. What prompted us to identify some gaps in the subject area and fill them in the current study.

Thus, it has been proven that fuel consumption on marine vessels depends on many factors, such as the type of vessel, its dimensions, speed, carrying capacity, sailing conditions (weather conditions, sea surface, etc.), as well as the condition of the vessel and the operation of its engines. The main approaches that are used to solve the problem of laying a route taking into account hydrometeorological conditions include the isochronous method, dynamic programming, variational calculus, the use of path-finding algorithms and heuristics. The use of artificial intelligence and machine learning has become widespread in recent years.

Unlike models that use hydrodynamic equations of ship motion and computational methods, when using cellular automata, one does not have to deal with estimations of calculation accuracy, convergence of procedures, and stability of numerical schemes. A two-dimensional cellular automaton is represented by a set of finite automata on the plane, denoted by integer coordinates (i, j), each of which can be in one of the states. At each step of calculations (made at time t), the cellular automaton bypasses the entire array of cells and transfers it to another state. Usually, a cellular automaton works on a grid with squares, which are its components. Sometimes hexagons are chosen as such components. This work also uses a hexagonal grid (hexagonal lattice). The application of cellular automata-based system models is due to the fact that for their functioning, it is necessary to describe a set of cell states and the transition function between them. However, clear models do not cover all possibilities of application of cellular automata. In situations characterized by uncertainty, incompleteness, or blurring, when the state of cells and transition functions cannot be clearly described, the theory of fuzzy sets comes in handy. Then the cell states are given in a fuzzy form, where the degree of fuzziness is given by the corresponding membership function. Also, when applying fuzzy cellular automata, not probabilistic but fuzzy rules are used. In such systems, the membership function is set, so that at the next step the cell will change its color to another. Or a rule is added that a cell with a certain membership function can change its color to the opposite, and the other rules of this cellular automaton remain unchanged. An important property of cellular automata is the change in the neighborhood of a cell over time and/or space. Fuzzy cellular automata can use the rule that the new state of a cell is affected by the new states of neighboring cells. For example, in 2 by 2 blocks, the states of the cells depend on the state of the cells inside the block and on the same adjacent blocks. Therefore, it is promising to develop models of cellular automata with fuzzy control based on the mathematical apparatus of fuzzy sets and fuzzy logic.

Thus, the issue of synthesizing the ship's route, which is optimal according to certain parameters, especially for the conditions of the online mode, has not been fully resolved. The analysis of studies on the development of the ship's fuel-minimization route, taking into account the forecast of weather conditions, reveals the following. First, some of the considered methods and models give insufficiently accurate results due to their failure to take into account certain hydrometeorological factors, such as currents, ice-covered waters, new ice areas, etc. Secondly, most of the considered methods do not take into account the uncertain nature of weather forecasts. Thirdly, a significant part of algorithms and methods cannot function on a real time scale, which is explained by high computational complexity. And finally, certain models and methods do not provide for the introduction of the importance of weighting factors that will be assigned to individual weather factors that affect the formation of the route of the ships. Thus, the given information makes it possible to use fuzzy cellular automata to calculate the ship's route, which in a certain sense eliminates most of the disadvantages inherent in the considered approaches.

3. The aim and objectives of the study

The goal is to improve the method of forming the optimal route in the e-Navigation system, taking into account the forecast of weather conditions. This will make it possible to ensure minimal fuel consumption, with minimal risk to the vessel and cargo, and take into account variable hydrometeorological conditions in real time.

To achieve the goal of the research, the following tasks must be completed:

– to devise a long-distance vessel passage plan with a forecast of weather conditions for discrete representation in time and space;

– to analyze the factors and compile a formalized statement of the problem to optimize the traffic route based on fuel consumption;

– to construct a method for preparing a safe optimal route for the passage of vessels based on a fuzzy cellular automaton.

4. The study materials and methods

The object of our study is the process of long-distance passage of ships from the port of departure to the port of destination, taking into account weather conditions on the sailing route.

The «vessel-environment» system functions under conditions of non-stochastic uncertainty. Each voyage is unique, which determines the expediency of using models based on fuzzy cellular automata (FCA) in the methods of forming a safe, optimal fuel consumption route of the passage of ships taking into account the forecast of weather conditions [19]. The use of fuzzy sets in the model of the optimal fuel consumption route of the vessel makes it possible to take into account many situations (development of the navigational situation) and their uncertainty in a single simulation. In addition, the application of the mathematical apparatus of fuzzy sets can be applied to data fusion procedures. Fuzzy set operations can be used for this task because their formal structure is suitable for describing fuzzy data coming from ship information sources and shore services.

The main advantages of a fuzzy cellular automaton are:

– the ability of elements to move in space and apply the concept of state to a new position;

– the state of each cell is updated due to the execution of a sequence of discrete constant steps in time;

– the variables in each cell are updated synchronously, based on the values of the variables at the previous stage;

– the rule for determining the new state of a cell depends only on its local values from some neighborhood of this cell.

Research hypotheses:

1. When forming a safe optimal route for the passage of a vessel, a decrease in the vessel's speed is allowed.

2. The ship's route is represented by the movement trajectory and the change in linear speed on a finite number of sections with a constant course value.

3. To determine the state of cells of a fuzzy cellular automaton and the transition function between them, a system of production rules and membership functions is applied.

The assumption of using the proposed method is a discrete version of the operation, which is caused by a discrete representation in time and space of the forecast of weather conditions used as initial data.

The mathematical apparatus of conventional cellular automata, fuzzy sets, and fuzzy logic was used as a research method. The use of elements of fuzzy mathematics makes it possible to describe the subject area, solve dynamic tasks with fuzzy input data, and take into account the experience of shipmasters while performing complex calculations when it is impossible to perform exact mathematical computations.

5. Results of studying the influence of weather on the construction of the optimal route of ship passage

5. 1. Discrete representation in time and space of planning the passage of a ship over long distances with a forecast of weather conditions

A recommended route $\left(W_i^{rec}\right)$ is a route that does not contain sections that pass through obstacles or do not meet the requirements of navigation safety [17]. The admissibility of the recommended route depends on the type, technical characteristics, and loading of the vessel. The safety of sailing is also affected by weather conditions and the choice of speed and course while passing a section of the route.

In turn, it is possible to describe W_i^{rec}:

$$W^{rec}=\left\{Cord_{st}^{W^{rec}},Cord_{fin}^{W^{rec}},Cord_{i}^{W^{rec}},wid^{W^{rec}}\right\}, \quad (1)$$

where $Cord_{st}^{W^{rec}}$, $Cord_{fin}^{W^{rec}}$, $Cord_{i}^{W^{rec}}$ – coordinates of the initial, final, and intermediate (turning) points of the path; $wid^{W^{rec}}$ – path width.

A safe route for which high values of quality criteria are achieved is considered to be the optimal route for the passage of a vessel. Such criteria include:

– fuel economy;

– reduction of sailing time;

– the compliance of the sailing time with that specified in the transition plan.

Fuel economy is a criterion used in the formation of a safe optimal route for the passage of a vessel, provided that the voyage task allows a decrease in the vessel's speed. For this, the shipmaster switches the ship's movement parameters to the economic speed mode V_e^{sh}.

Economic speed V_e^{sh} is the speed at which the maximum economy of fuel and lubricants is ensured. However, the following conditions must be observed:

– availability of a reserve of running time, which allows the vessel to arrive at the port of destination on time;

– long-term operation under this mode will not reduce the reliability of the power plant.

The main indicator of economy during V_e^{sh} selection is road fuel consumption g_{wr}^{sh} (when $V^{sh}>0$):

$$g_{wr}^{sh}=\frac{G_{wr}^{sh}}{V^{sh}\cdot t_{wr}^{sh}}, \quad (2)$$

where G_{wr}^{sh} – normative fuel consumption for passage of the route section by the vessel; V^{sh} – the speed of the ship on the given section of the route; t_{wr}^{sh} – transit time of the vessel on a given section of the route.

The standard fuel consumption for the passage of the route G_{wr}^{sh} by the vessel is taken according to the tables calculated in advance. It should be taken into account that the values for these tables are calculated for a vessel in which the hull, main engines, auxiliary mechanisms, propellers (thrusters) are in good technical condition. The ship's systems and mechanisms are serviced by qualified personnel. Normative fuel consumption requires compliance with the calculated modes of movement of the vessel.

5. 2. Analysis of factors and the formal statement of the problem to optimize the traffic route based on fuel consumption

The efficiency of fuel consumption is influenced by operational factors [18]:

– engine temperature regime;

– engine operation mode;

– wear and tear of nodes and parts;

– technical condition, as well as external factors and conditions of movement of the vessel:

– wind direction and speed;

– direction of propagation, period, and height of wind waves;

– direction of propagation, period, and height of the wave;

– the direction and speed of the current, which affect the actual speed of the vessel V^{sh}.

The first group of factors refers to indicators of the technical condition of the vessel. The impact of these factors can be minimized by continuously monitoring the technical condition of the vessel and responding to deviations from acceptable values. The factors of the second group affect the choice of the rational choice, the economic speed V_e^{sh}. Therefore, the algorithms for planning the optimal route must take into account these two groups of factors. Each time the calculated route can be considered unique. The reason for this is that the indicators of the technical condition of the vessel will differ from the previous ones. From the point of view of probability theory, the conditions of the experiment cannot be considered the same. For such conditions, it is advisable to describe the indicators of the technical condition by fuzzy sets with triangular membership functions. Similarly, the hydrometeorological conditions during the voyage are always different. This also speaks in favor of using the apparatus of fuzzy sets to describe the specified factors. In addition, most of the characteristics coming from shore services or sensors of ship systems already contain elements of non-stochastic uncertainty. For example, it is indicated that the wind is southwesterly at a speed of 25–30 m/s or the air temperature is 4–6°. Also, certain factors are represented in the form of qualitative and not quantitative characteristics, which, together with the spread of parameters, gives every reason to use the apparatus of fuzzy sets for representing factors when setting an optimization problem. With the help of the specified factors, it is possible to implement the necessary mode of operation of the main engines on different sections of the route in accordance with the calculated modes of movement of the ship. At the same time, it is proposed to use the conventional system of cruise fuel consumption rationing for most shipping companies. External conditions are taken into account by collecting and analyzing weather forecasts from shore services and ship systems. This information is usually provided as predicted parameter values for grid nodes projected onto the sailing area. This grid has a fixed step in coordinates and time.

The formal statement of the task of optimizing the driving route based on fuel consumption can be represented in the following form. Let the ship's route be represented as the trajectory of its movement and the change in linear speed on a finite number of sections with a constant course value. Then the ship's route is described by a vector:

$$W_{route}^{sh}=\left\{\left(h_1,S_1,V_1^{sh}\right),\left(h_2,S_2,V_2^{sh}\right),\ldots,\left(h_i,S_i,V_i^{sh}\right)\right\},$$
$$W_{route}^{sh}\in W^{rec}, \tag{3}$$

where $h_i, V_i^{sh},\ i\in\overline{1,n}$ is the course and speed of the ship on the i-th section of the route; S_i, $i\in\overline{1,n}$ – the length of the i-th section of the route.

This vector W_{route}^{sh} makes it possible to unambiguously determine the route of the ship. To determine V_e^{sh}, it is necessary to consider the specified and actual speed of the ship. The set speed V^{eng} is determined by the operation of the engines, so it is directly related to fuel consumption. The actual speed V^{sh} is the set speed taking into account external conditions and the direction of movement of the vessel. The actual and set speed can be considered equal only in the absence of external influences – turbulence, wind, and current. Then the vector W_{route}^{sh} takes the form:

$$W_{route}^{sh}=\left\{\begin{matrix}\left(h_1,S_1,V_1^{eng},INF_1\right),\\ \left(h_2,S_2,V_2^{eng},INF_2\right),\ldots,\left(h_i,S_i,V_n^{eng},INF_i\right)\end{matrix}\right\},$$
$$W_{route}^{sh}\in W^{rec}, \tag{4}$$

where INF_i $i\in\overline{1,n}$ is the vector of external influences – wave $\left(inf_i^{wave}\right)$, wind $\left(inf_i^{wind}\right)$, and current $\left(inf_i^{curr}\right)$:

$$INF_i=\left\{inf_i^{wave},inf_i^{wind},inf_i^{curr}\right\}. \tag{5}$$

The task of forming a route that provides fuel economy can be represented as:

$$G_F\left(W_{route}^{sh}\right)\to\min_{W_{route}^{sh}\in W^{rec}}, \tag{6}$$

where $G_F\left(W_{route}^{sh}\right)$ – the objective fuel consumption function for the route W_{route}^{sh}, calculated using the known characteristics of the engines – route fuel consumption g_{wr}^{sh} at a given speed V^{eng}.

Solving the problem of route formation that ensures fuel economy (6) using numerical methods is complicated, namely:

– this task refers to optimization tasks of nonlinear programming;

– the «vessel-environment» system has a wide range of values that it can reach regardless of the number and degree of influence of both external and internal factors. This leads to a rather limited choice of approaches that have methods of forecasting the development of the navigational situation;

– a small volume of data reduces the probability of obtaining an accurate forecast;

– in the process of modeling the «vessel-environment» system using a set of differential equations, the physical reality, which is often discrete in nature, is replaced by a continuous model. When moving to numerical methods, space and time in this continuous model are made discrete again, which, after their implementation in computer systems, causes a decrease in the speed of issuing results.

From here, it is necessary to immediately build, first, discrete models. And, secondly, models should formalize a set of possible states and rules by which these states change each other over time and provide the possibility of working under conditions of uncertainty.

5. 3. The method of forming a safe optimal route for the passage of vessels based on a fuzzy cellular automaton

A fuzzy *FCA* cellular automaton is a set of objects:

$$\left\{W,S,N,R^{FCA}\right\}, \tag{7}$$

where W is a discrete metric lattice of a fuzzy automaton; S – finite set of possible cell states; N – a finite set that defines the cells that affect the new state of the current one; R^{FCA} – *FCA* Product Rules.

For the discrete metric lattice of the automaton, a hexagonal lattice is used, since the neighboring cells of the hexagonal cell are included in the Neumann region (Fig. 1).

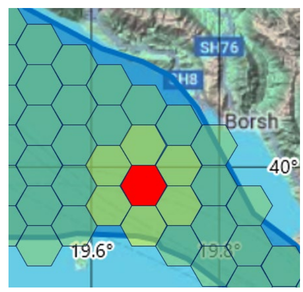

Fig. 1. Hexagonal lattice of fuzzy cellular automaton

The *FCA* model of formation of a safe, optimal fuel consumption route of the passage of vessels taking into account the forecast of weather conditions provides for the division of the navigation area:

$$MR=\sum_{1}^{n}W_i^{rec}, \tag{8}$$

in which the vessel is transferred to cells (Fig. 2).

Cell sizes correspond to route segments of the same length in discrete time steps. These cells form a discrete metric lattice of the automaton. The position of the ship, its speed and other parameters of the environment are fuzzified.

The state of each cell $s_i\in S$ at the moment of time t is described by the linguistic variable «road fuel consumption», which takes the values «low», «medium», «high». These values are quantified by some fuzzy subsets g_{wr}^{low}, g_{wr}^{mid}, g_{wr}^{high} of the universum S using vector membership functions $\mu_{g_{wr}^{low}}(s), \mu_{g_{wr}^{mid}}(s), \mu_{g_{wr}^{high}}(s)$. In addition to the fuzzy state of the cell, which defines its state, each cell can be characterized by several properties that constitute the corresponding variables of the navigation environment at the point associated with the cell. These properties are used by the transition function of the cellular automaton in order to simulate changes in road fuel consumption under various external factors.

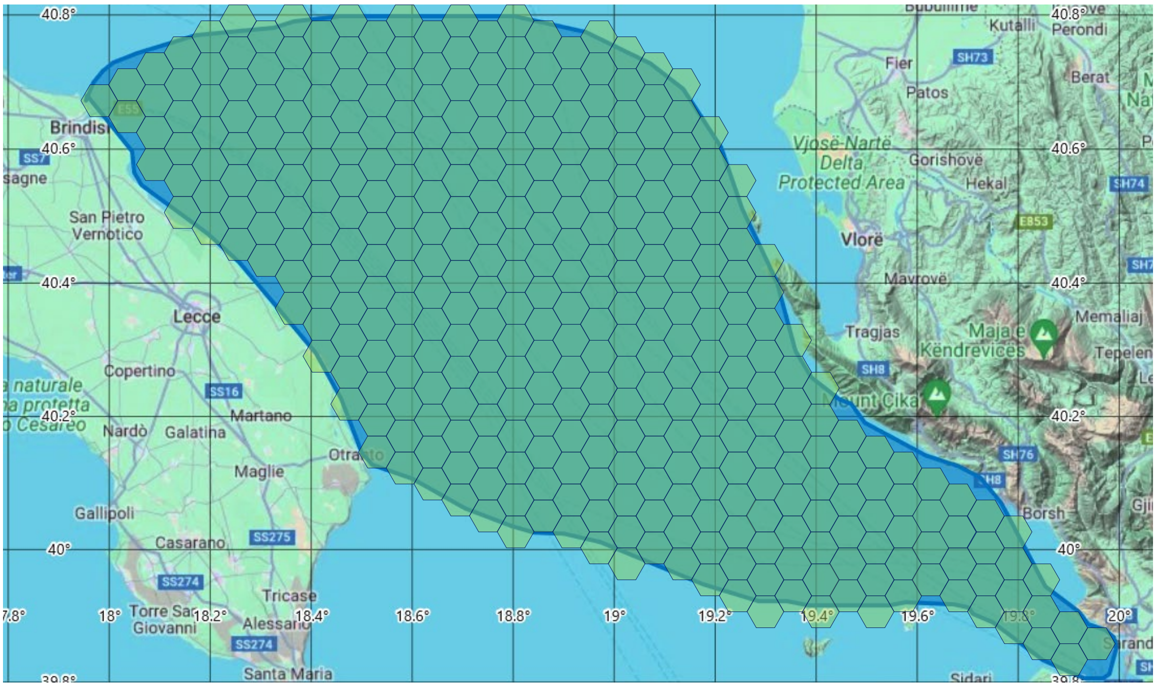

Fig. 2. Hexagonal lattice of fuzzy cellular automaton

For example, each cell will be characterized by wind direction and speed, propagation direction, wind wave period and height, and current direction and speed. The vessel is described by its condition and speed. The condition determines the characteristics of the vessel (engine operation mode, wear of components and parts, technical dimensions of the vessel). All these quantities are expressed by some fuzzy sets.

The algorithm of the fuzzy automaton is formed by the fuzzy production rules R^{FCA}. At the initial time t_0, the state of each cell $s_i \in S$ has some initial value of the membership function. Then the automaton works in steps.

At the step numbered $t_0+\Delta t$, R^{FCA} calculates new values for the membership functions of neighboring cells:

$$s_i : [S \times N] R^{FCA} \xrightarrow{t_i+\Delta t} \mu_{g_{wr}} (s_{i+1}). \quad (9)$$

The generalized method of forming a safe, optimal fuel consumption route of the passage of ships, taking into account the forecast of weather conditions, consists of the stages shown in Fig. 3.

A demo version of the program was developed, which simulates a safe passage route of ships taking into account weather conditions, optimal in terms of fuel consumption, built on the basis of cellular automata, fuzzy sets, and fuzzy logic (Fig. 4–6).

The program takes into account the technical condition of the ship and some of the meteorological factors affecting its actual speed V^{sh}.

Fig. 4 shows the plan for the passage of the ship from point S to point F. The calculated route is safe and optimal in terms of fuel consumption of the route of the passage of ships, taking into account the weather conditions at the time of planning.

In the process of moving along the route, the ship received information that the navigational situation had changed near the final point of the route. And this obstacle could affect the ship when it reaches the indicated point at the pre-calculated time (Fig. 5).

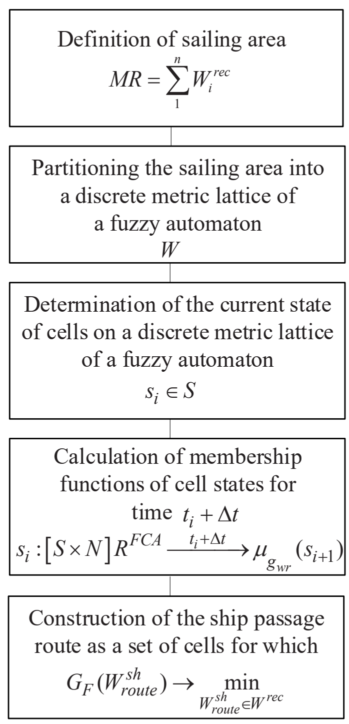

Fig. 3. Main stages of the method to form a safe, optimal fuel consumption route for the passage of ships taking into account the forecast of weather conditions

Next, based on the analysis of the weather forecast and the information received from the coastal services, a meteorological hazard area is predicted for the grid nodes projected onto the navigation area. These data are the basis for rebuilding the ship's route (Fig. 6).

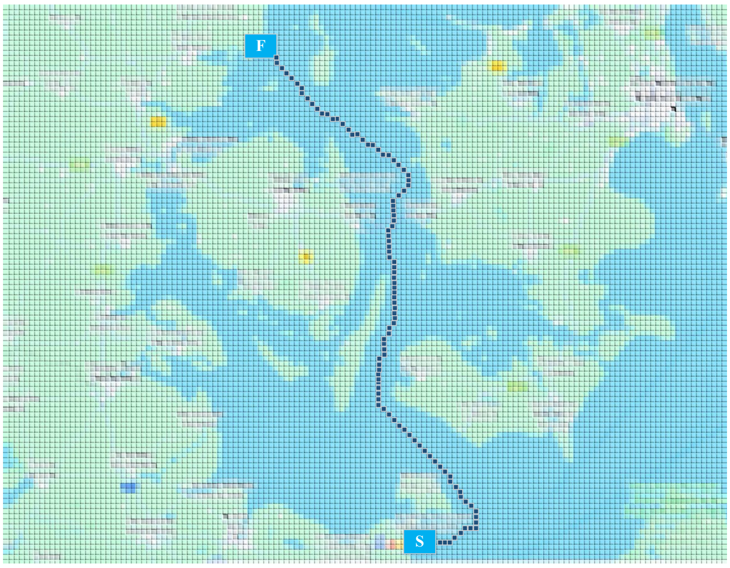

Fig. 4. Plan of the vessel's passage from point *S* to point *F*

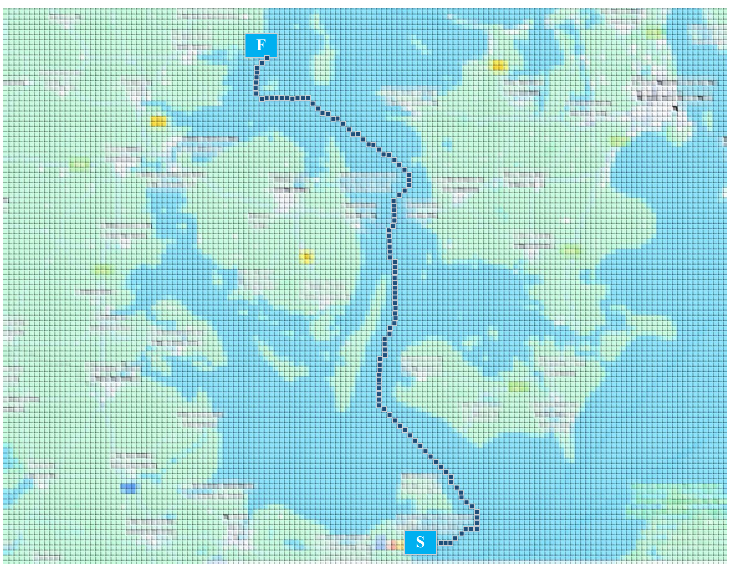

Fig. 5. Vessel's route taking into account navigational hazard

Fig. 6. Route of the vessel, taking into account meteorological conditions

The constructed fuzzy cellular automaton based on fuzzy rules allows the use of descriptive uncertain knowledge about the behavior of the ship-environment system. It is proposed to describe the ship's parameters and environmental factors by triangular membership functions, which ensures the formalization of the uncertainty of the navigational situation and allows describing possible navigational situations. The uncertainty of the state of motion is described using fuzzy definitions of vessel parameters and the introduction of fuzzy operations into the model update procedure. The use of a fuzzy cellular automaton makes the proposed model suitable for imprecise data fusion in the e-Navigation system.

6. Discussion of results of the research on the formation of the optimal transition route taking into account the weather forecast

The planning of the passage of the ship over long distances with the forecast of weather conditions, unlike that given in [4, 11], is represented in time and space in a discrete form. At the same time, the sections of the recommended route bypass any obstacles and clearly ensure the fulfillment of the safety requirements of sailing. On the optimal transition route, the necessary values of the quality criteria are achieved, namely economy and sailing time, as well as the compliance of the sailing time with the specified in the transition plan. Each section of the route is described by the same weather conditions, which makes it possible to obtain the optimal fuel consumption transition plan at each individual section, which is confirmed by expression (2). A limitation is the relatively small number of areas where the same weather is defined. At the same time, forecasted weather values on the route often differ from the actual ones, which will require adjustments to the calculations made at the stage of planning the passage of the vessel. The disadvantages of the proposed method of planning the passage of the vessel are the lack of clear boundaries defining different classes of weather, and, accordingly, the subjectivity of determining the number and length of individual sections of the passage route. The area of further research is the classification of weather conditions for a clear and unambiguous definition of areas for calculating the optimal route.

In the formal statement of the task of optimizing the traffic route based on fuel consumption, an analysis of operating factors and external conditions affecting fuel consumption on various sections of the route in accordance with the calculated modes of the ship's movement was carried out. When formalizing the ship's route, in contrast to the one given in [3, 5, 6, 8], the trajectory of its movement and the change in linear speed on a finite number of sections are represented with a constant course value, which makes it possible to unambiguously determine the route of the ship's movement. Correctness of our result is confirmed by the introduced expression (4). Limitations are that the actual and set speeds will be considered equal only in the absence of external influences – turbulence, wind, and current. It was established that due to the non-linear nature of the route formation optimization problem, it is difficult to apply numerical methods. Formula (6) testifies to the optimality of solving the problem of route formation, which ensures fuel economy, the use of which limits the choice of approaches for forecasting the development of the navigational situation and, with a small amount of initial data, reduces the accuracy of the forecast. In addition, the transition from discrete to continuous models and vice versa reduces the speed of the model. Further development of the work of this model is the need to formalize a set of possible weather conditions and the rules for their change over time, and to ensure the ability of the model to work under conditions of uncertainty.

Therefore, for the formation of a safe, optimal fuel consumption route of the passage of ships, taking into account the forecast of weather conditions, a possible way to achieve the set goals is the use of fuzzy sets and fuzzy cellular automata. This approach, in contrast to the one proposed in [9–12], takes into account the uncertainty and evolution of the navigation situation. This metric automaton lattice is a discrete hexagonal lattice. The proposed *FCA* model for the formation of a safe, optimal fuel consumption route for the passage of vessels, taking into account the forecast of weather conditions, involves the division of the navigation area into cells. As a limitation of the research, it is accepted that the cell sizes correspond to segments of the route of the same length in discrete time steps. The results are explained and confirmed in Fig. 2. These cells form a discrete metric lattice of the automaton. Each cell is described by a linguistic variable «road fuel consumption» with certain values and can be characterized by a transition function to simulate changes in road fuel consumption under different external factors.

The constructed fuzzy cellular automaton based on fuzzy rules allows the use of descriptive uncertain knowledge about the behavior of the ship-environment system. The parameters of the ship and environmental factors are described by membership functions, which provide formalization of the uncertainty of the navigation situation and allows describing possible navigation situations. The uncertainty of the traffic state is described using fuzzy definitions of vehicle parameters and introducing fuzzy operations into the model update procedure. The use of a fuzzy cellular automaton makes the proposed model suitable for imprecise data fusion in the e-Navigation system.

The main restrictions determining the choice of routes are obstacles (areas of land in shallow water), as well as safety requirements for navigation.

The area of further research is the development and investigation of a program that simulates a safe passage route of ships, optimal in terms of fuel consumption, built on the basis of fuzzy cellular automata, taking into account the technical condition of the ship and weather conditions. To compare the route built according to the model of fuzzy cellular automata, it is planned to develop a program that will simulate the optimal route of the ship with the specified restrictions, built according to the Pontryagin maximum principle or based on the dynamic forecasting method.

7. Conclusions

1. It is advisable to represent the passage of a ship over long distances with a forecast of weather conditions in time and space in a discrete form, each of which sections does not pass through obstacles or does not ensure the fulfillment of navigation safety requirements. When forming a safe optimal route for the passage of the vessel, a decrease in the speed of the vessel is allowed.

2. Taking into account in the optimization model operational and external factors affecting the movement of the ship, which is distinguished by their representation in the form of fuzzy sets with appropriate membership functions, makes it possible to represent the route of the ship as a trajectory of its movement and a change in linear speed on a finite number of sections with a constant course value. Solving the problem of forming the optimal fuel consumption route using numerical methods is complicated and requires the construction of discrete models. In addition, the problem of model operation under conditions of uncertainty requires an immediate solution.

3. Our paper proposes a method for forming a safe, optimal fuel consumption route for ships, taking into account weather conditions, the foundation of which is conventional cellular automata, fuzzy sets, and fuzzy logic. The use of elements of fuzzy mathematics allows solving dynamic problems with fuzzy input data and taking into account the experience of shipmasters when performing complex calculations when it is impossible to perform exact mathematical computation. To determine the state of cells of a fuzzy cellular automaton and the transition function between them, a system of production rules and membership functions has been applied.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The software tools used are available at https://(accessed March 12, 2024). The data presented in this study are available upon request from the corresponding author.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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