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FUZZY EXPERT SYSTEM FOR ADAPTIVE VESSEL TRAFFIC CONTROL ON ONE-WAY SECTION ON NAVIGABLE CANAL

Summary. This paper analyses the management process of the vessel traffic control on one-way section on navigable canal with the adaptive time-sequential filter (traffic lights). One-way section on canal significantly decreases waterway capacity and requests special attention in control and regulation of the vessel traffic. The vessel traffic is a stochastic variable, and the vessel traffic control needs to be flexible and adaptive in order to achieve the required traffic flow with minimal delays. On the one-way section, two independent variable vessel flows from opposite directions are encountered, and fixed (predefined) signal plans lead to an increase in vessel delays. An appropriate solution is development of a Fuzzy Control System (FCS) for the vessel traffic control. A control algorithm is designed according to a set of linguistic rules that describes input parameters for the control strategy. The estimated and approximate input parameters are implemented in the algorithm as fuzzy sets. The final result of the developed algorithm is the traffic light scheme (duration of green light for certain direction). The presented control system can be used as an adaptive automatic control system for the vessel traffic control processes on navigable canals or on critical sections of other waterways.

1. INTRODUCTION

Human civilization development and shipping have been connected for the past 5000 years. From small ships on rivers in Mesopotamia and the east Mediterranean to the modern container ships, water transport has been rising and has become a transport mode of global importance [1]. The vessel traffic intensity is expected to increase during this decade and beyond [2], especially in the Asia driven by economic growth of China and India.

Increase of the vessel traffic volume also affects the congestion increase and the risk of accidents, especially in the areas of restricted navigation (ship lock, port entrance, one-way section and dredging zone). The process of restricted or regulated navigation takes place within the area with restrictions or difficulties. The one-way section exemplifies zone of the restricted and regulated navigation that requires special attention.

This paper presents design and development of the vessel traffic control system on the one-way sections of inland waterways based on fuzzy logic.

2. BACKGROUND

With increase of vessels' size and vessel traffic density, a natural need for the waterway capacity analysis, increased navigation safety or the reduction of the risk of an accident has appeared [3]. The logical solution is to establish active positioning, monitoring, assessment, decision making, notification and management of vessel traffic in areas of restricted navigation. Solution evolution of this problem begins with waterway capacity and risk assessment analyses. Analytic methods and simulation models for the waterway capacity determination, along with vessel traffic flow and waterway capacity analyses, are being developed and applied constantly [4 - 6].

One-way sections are bottlenecks of the transportation system, becuase due to their dimensions, simultaneous two-way navigation is not allowed. This restriction may be applied to all vessels or just to vessels whose size exceeds the limit for two-way navigation on the section. Access to the one-way section is restrictive. It is permitted to move only in one direction, either upstream or downstream, but not in both directions simultaneously. There is an evident progress in the development of analytical and simulation models for the waterway capacity determination and the vessel traffic analysis [7, 3, 8 - 10]. Moreover, considerable attention and research are focused on scheduling issues in the maritime transport area, at macro and micro level. Traffic safety and vessel traffic efficiency are the two important principles of vessel traffic scheduling in ports. In certain port areas, passage of only one ship is possible, and as our requests strive to the minimum berths waiting time and the minimum waiting of the vessel to be processed, it is necessary to solve the ship scheduling problem in the port [11 - 13].

Unlike maritime navigation, navigation on inland waterways by its nature is faced with restrictions and continual changes in navigational conditions. Before making decisions regarding the vessel traffic management and control, a detailed analysis of navigation conditions is required [14]. In recent research, new models for addressing the congestion problem and different control strategies [15], or a microcosmic simulation models of vessel traffic in the inland waterway [16] are being considered. However, the problem of vessel traffic management and control on navigable canals on the inland waterways network has not been considered in more detail, but there is a need for this problem analysis. Bačkalić studied traffic control techniques on navigable waterways with limited dimensions in function of their capacity [17]. Finding better control system in the terms of avoiding the accumulation of vessels in the queue at the entrance of the section and minimizing waiting times is the subject of this paper.

3. PROBLEM DESCRIPTION

3.1. Regulated navigation

During unrestricted navigation, the whole navigation process is entrusted to humans - the navigators. They independently manage their vessels according to regular navigation rules. On the contrary, within the area with restrictions or difficulties, the navigators manage their vessels with increased attention and permanent mutual communication (information on position, movement and intentions, and control decisions). In order to increase safety and capacity and reduce delays in the areas with restrictions or difficulties, it is necessary to introduce a regulated navigation.

Vessel traffic management at the regulated navigation is based on two subsystems - the navigators and the control system with crew and equipment. Decisions relating to vessel passage organization or ship locking are made by the control system, and navigators safely manage their vessels in accordance with the information and instructions received from the control system. The input values from the supervision area ("coverage area") of the control system or centre are number of vessels, direction of movement, speed, position, priority level, vessel dimensions, hydrological and meteorological data, and the output values are control decisions.

Control decisions can be classified according to importance as notification (least strict), recommendation (more strict) and order (the navigator must manage the vessel's moving strictly in accordance with received commands). In the one-way sections of the navigable canal, there are two navigation modes - restricted navigation and regulated navigation. In the restricted navigation mode, the navigators should agree on the passage through the one-way section with respect to the specific rules of navigation. In the regulated navigation mode, navigators manage the vessel movement in accordance with the orders received from the control system.

According to the method of organizing of vessel traffic and directing of control actions for vessels' passage through a one-way section, the control system in the regulated navigation mode can be as follows:

- system with direct communication between the control operator and the navigator and
- system with indirect control via communication the operator-signal device-navigator.

The system with direct communication requires full attention and commitment of all participants in the process of vessels' movement control in the supervision area. This control system functions similarly to air traffic control (VTS concept) [5].

The system with indirect control contains a control unit that represents a time-sequential filter (traffic lights) for the control of vessel traffic. The system requires the operator controlling the work of the control unit and the state of readiness in case of the control unit failure. The communication between the control centre and the navigator is carried out indirectly via the control unit by means of light signals or the display.

Depending on the applied operating plan of the control unit (the signal plan), there are control systems with the following:

- precisely defined cycle duration (fixed signal plan) and
- adaptive signal plan based on fuzzy logic.

The correct determination of the cycle duration (the signal plan) requires knowledge of the technological process of vessel traffic and the value of the capacity of the observed waterway section.

3.2. Concept and characteristics of navigation on the one-way waterway section

Technological process of vessel traffic in one-way section of waterway

Moving of vessels in navigable canal and especially in one-way section is rather difficult due to restricted dimensions of waterway. Technological process of vessel traffic on the navigable canal is represented by set of rules and activities for control of navigation in canal, in order to perform rational and safe utilization of waterway capacity and reduce delays of vessels. This process depends on [17] the following:

- technical and exploitation characteristics of the canal and objects,
- technical and exploitation characteristics of fleet,
- traffic density,
- priority of vessels,
- an appropriate traffic management scheme,
- navigation conditions on the waterway and
- hydrological and meteorological conditions.

According to the vessel traffic management scheme and exploitation conditions, on the one-way waterway section there are different types of the technological processes of vessel traffic: singly passing one by one vessel (section with or without the widening for passing over), group vessel passing (certain number of vessels per group) and passing of vessels with time-sequential regulation of entries in section (time-sequential filter with light signalization - traffic lights). The choice of the vessel traffic management scheme, i.e. the technological processes of vessel traffic, depends primarily on traffic intensity and priority of vessels for passage. Vessel traffic must be organized in order to avoid long waiting of vessels in queues at the entrance and vessel amassing.

Capacity of the one-way section of waterway

Capacity is one of the most important characteristics of transportation systems. It should be distinguished from the traffic density. Magnitude of the waterway capacity, as a substantial characteristic of each traffic way, has a great importance for institutions and services that perform control and regulation of vessel traffic. Analytical methods for waterway capacity determination give average values of capacity [18]. When the vessel traffic density on observed waterway section or waterway as whole reaches the limit values under certain technical and exploitation conditions, it is necessary to determine the waterway capacity for changed mode of exploitation (i.e. for changed technical characteristics and/or mode of exploitation) [19].

Simulation models for capacity determination and analysis of the vessel traffic on the one-way waterway section are developed according to the type of the technological process of vessel traffic on observed section [17]. Simulation models consist of model segments or sub-models as follows: sub-models of vessel traffic and sub-models of vessel moving control (for each direction), and sub-model of the control and operation of traffic light controllers.

Simulation models of the vessel traffic on the specific canal sections in function of the waterway capacity are developed according to the type of the technological process of vessel traffic on observed real section - two-way section l_d=35000 m and one-way section l_j=8030 m [17]. Simulation experiments are performed for various cases of vessel traffic densities, under constant basic parameters (vessel length L=77 m; navigation speed v=8 km/h; period duration t=30 days; vessels arrivals correspond to Poisson's distribution [10], FIFO/FCFS queue priority). For models with time-sequential regulation of entrances, four cycle durations were used - 30, 60, 120 and 240 minutes. During capacity determination, it was assumed that the traffic densities from both directions are approximately equal. In the table 1 and Fig. 1, the results of experimental determination of waterway capacity by simulation are shown.

Table 1

Results of experimental determination of waterway capacity by simulation

Section	Two-way section	Ship lock	One-way section without widening	One-way section with widening
Capacity [vessels/month]	13,232	1,091	534	882
Section	One-way section 30 min of green light	One-way section 60 min of green light	One-way section 120 min of green light	One-way section 240 min of green light
Capacity [vessels/month]	2,023	3,158	4,382	5,435

Fig. 1 shows basic results of simulation experiments (capacity, maximal number of vessels per queue and average time delays in queues) for models of one-way section for different ways of control (alternating passing with or without widening and time sequential regulation of entrances for different duration of green light).

4. SYSTEM CONTROL BASED ON FUZZY LOGIC

Fuzzy logic control is based on application of the fuzzy set theory and the fuzzy logic reasoning, and it is widely known as a control method that does not request a precise mathematical model of the control object. Fuzzy control is practically an attempt to transfer the imprecise and estimated work descriptions of some system and their presentation into the computer by simple rules. In this way, knowledge of the expert-operator from specific field can be used to achieve effective control of specific system.

It is intended to be implemented in a PLC (Programmable Logic Controller) program. There are examples of improving PLC and SCADA (Supervisory Control and Data Acquisition) control logic in irrigation canals [20], but this paper presents a rare application of artificial intelligence in navigable canals. However, there are several studies that introduced fuzzy logic and optimization techniques in the field of managing a ship lock [21 - 23] and risk assessment and vessel scheduling [24, 25].

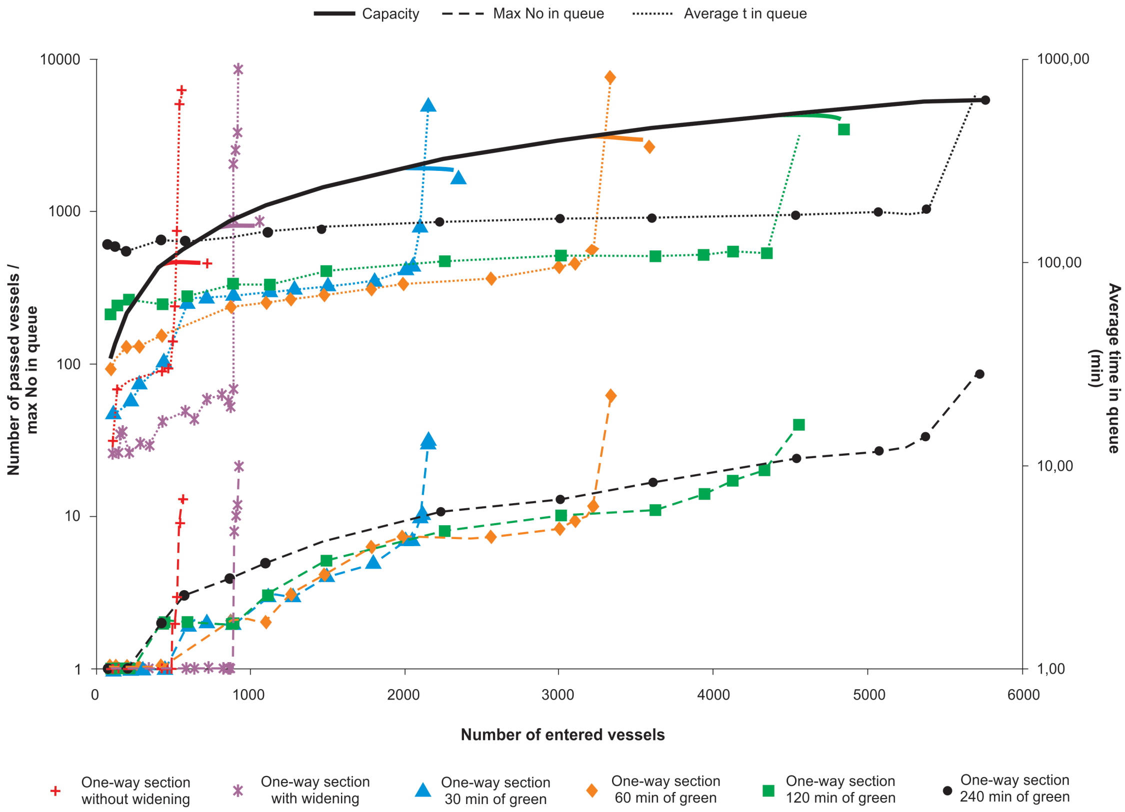

Fig. 1. Basic results of simulation experiments (capacity, maximal number of vessels per queue and average time delays in queues) with models of the one-way section

Fuzzy control system (FCS) is a control system on general level and it uses qualitative descriptions in terms of human language. Fuzzy linguistic control rules are the basis of fuzzy control system, and they are usually constructed at the beginning together with defining fuzzy variables and linguistic values they can take. These rules are collective control knowledge (together with knowledge that originates from operator's experience). In this way, we formed "IF-THEN" linguistic rules. "IF" part of the rule is named as a premise part of the rule condition, and its function is to define the control conditions. "THEN" part of the rule is named as a part of the rule conclusion, and its function is defining actions on the control system.

Construction of the fuzzy logic system consists of five steps:

Step 1: Definition of the input (measured) and the output (controlling) variables for the certain states of the process that is controlled, i.e. determination of which control action should be applied in certain states of the process.

Step 2: Defining of conditional converter, in other words determination in which way variable values of process state are expressed as fuzzy sets.

Step 3: Control rules construction - choosing rules that are applied under certain circumstances. In practice, Steps 2 and 3 are being implemented simultaneously, because it is very difficult, independently of each other, to define the rules and to choose the appropriate fuzzy values for all variables.

Step 4: Defining of fuzzy methods: AND/OR, implication and aggregation methods and algorithm developing for fuzzy reasoning. Exit results are fuzzy sets (fuzzy control action).

Step 5: Definition of the defuzzification method according to which fuzzy control action is transformed into non-fuzzy (precise) control action. In practical applications, fuzzy value cannot be used for control variable so it must be “defuzzified” to crisp value.

5. FUZZY CONTROL SYSTEM FOR ADAPTIVE VESSEL TRAFFIC CONTROL

5.1. Basic characteristics of fuzzy system for controlling vessel traffic on one-way section

In conditions of indefiniteness, basic problems at regulation of navigation on one-way section with time-sequential entrance regulation are as follows:

- determination of moment to switch on/off the system for vessel traffic process control and
- determination of cycle duration for allowable or forbidden entrance in section (for both directions) in dependence of traffic density.

Disadvantageous situations can be raised when cycle duration is precisely defined in advance and present traffic densities differ from predicted ones. Change of signal plan or determination of appropriate traffic densities for defined signal plan can be problematic too. These problems can be solved if we apply fuzzy controller for determination of moment for switch on/off the system for vessel traffic process control and for determination of cycle duration of time-sequential filter of entrance regulation in a section (for both directions).

The length of a one-way section can vary from a few kilometres to tens of kilometres. The developed FCS was designed and tested for the one-way section 8-km long. In addition, it is assumed that all vessels are similar and allowed navigation speed through the section is 8 km/h (assumption made for simulation purposes).

5.2. Design of fuzzy controlled vessel traffic light system

As one-way section is a single-channel system of servicing with opposite requirements, it is necessary to decide which side will be open and for how long. Therefore, the first step in designing is a definition of input and output (control) variables that will be used for calculations.

When considering input variables, some data can be extracted and calculated from information that is available on AIS (Automatic Identification System) or RIS (River Information Service) [26]. The input variables used in this research are chosen as follows: approaching time of the last vessel in the group of vessels that are present in the arrival time range of 120 minutes on each side and the total number of vessels in that two groups. Approaching time can be predicted with great accuracy from information on present position and actual speed (both available on AIS or RIS). Time period of 120 minutes is one of the parameters that can be adjusted depending on the actual needs and conditions.

Fuzzy system output is chosen to be a number from range [-240,240] which represents the duration of the green light in minutes. A sign indicates which side will be allowed access. If the number is negative, the vessels that are moving upstream have access granted, and if it is positive, the vessels, which are moving downstream, are permitted to access the section. In critical cases, where all parameters are identical on both sides, i.e. when output of fuzzy system is zero, priority was given to the downstream side in a very short period enough for passage of the vessels that are in the queue.

Three subjective categories are chosen concerning the distance of the vessel from entering the section, i.e. approaching time: “near”, “mid” and “far”. When it comes to the number of vessels, there are also three subjectively chosen categories: “small”, “medium” and “large”. For the output variable seven subjective categories are chosen to represent the period of light and direction: “long upstream”, “medium upstream”, “short upstream”, “undefined”, “short downstream”, “medium downstream” and “long downstream”.

Identifying the ways in which the variables are to be presented as a fuzzy set is usually determined by an expert or a system operator based on their experience and subjective assessment. Quantifying of variables in the system is performed with fuzzy sets and their membership functions. There are several types of membership functions that are most commonly used to describe the variables: triangular, trapezoidal, sigmoidal, etc. Sigmoidal membership functions (Eq. 1) are chosen for this application.

$$\mu(x) = \frac{1}{1 + e^{-a(x-b)}} \tag{1}$$

Variable *a* in Eq. 1 represents the growth rate, whereas *b* represents the inflection point of sigmoidal membership function. This function is used for several reasons: it is differentiable at every point in its entire domain; it permits to select different levels of non-linearity by choosing the amount and sophistication of the membership functions [27] and well describes the relationship between the membership function and the observed variables as shown on the basis of experiments and research [17].

Fuzzy values "*small*", "*medium*" and "*large*" of input fuzzy variables "*Number of vessels from the upstream side*" and "*Number of vessels from the downstream side*" are presented in Fig. 2. As the requirements on both sides are identical, therefore the membership functions are identical for both variables.

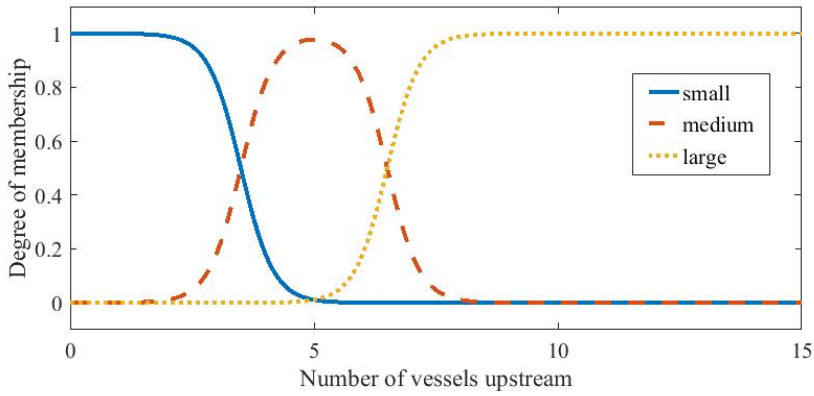

Fig. 2. Membership functions for input variables representing the number of vessels in range

Fig. 3 shows the membership functions of the input variables "*Arrival time of the last ship upstream*" and "*Arrival time of the last ship downstream*". These fuzzy variables are also identical owing to the problem symmetry, and arrival times are calculated in minutes.

Fig. 4 shows the membership functions of the output fuzzy variable of the controller. It gives the duration of the green light and the side on which the passage of the vessels will be allowed. All membership functions are subjectively selected based on various observations, tests and constraints.

The next step is to construct fuzzy control rules. The rules determine the control mode, i.e. which control action will be activated and for which values of the input variables. Once the variables are defined, construction of verbal rules needs to be done. Usually, this step is done for all combinations of input and control variables.

In the observed problem, 4 input variables, with 3 membership functions each, are defined. That leads to a total of 3^4=81 combinations, and the same number of fuzzy rules. One of the rules, as an example, is defined as follows:

IF ("*Number of vessels from the upstream side*" IS "*small*") AND ("*Number of vessels from the downstream side*" IS "*medium*") AND ("*Arrival time of the last ship upstream*" IS "*large*") AND ("*Arrival time of the last ship downstream*" IS "*small*") THEN ("*output*" IS "*short downstream*").

This large number of 81 rules in total seems cumbersome, but that is not the problem because the system that is to be controlled is extremely slow, and the changes in control actions are at hourly levels, so the time of calculation is not of great importance at all.

Fig. 5 graphically presents the calculation process with all fuzzy rules for chosen input values. The last column represents the output (control variable) and is calculated on the basis of the first four columns representing the number of vessels on the upstream side, the number of vessels on the downstream side, the arrival time of the last vessel upstream and the arrival time of the last vessel downstream, respectively.

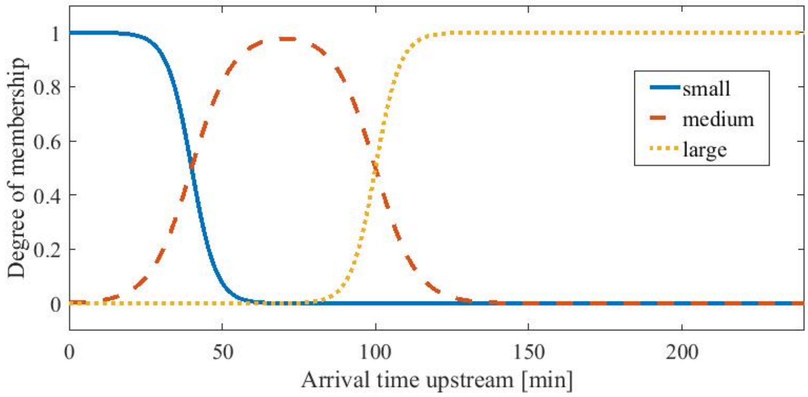

Fig. 3. Membership functions for input variables representing the arrival time of the last vessel in the observed range

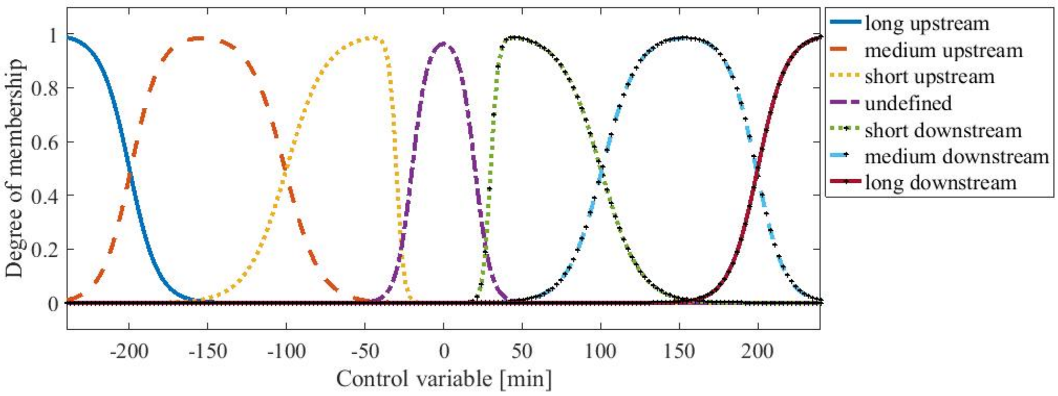

Fig. 4. Membership functions of output fuzzy variable

In order to thoroughly examine and select the combination of methods that yields the best results, different fuzzy inference methods are tested at the final stage. Two implication methods are tested: “minimum” and “product”. Three aggregation methods are tested: “maximum”, “sum” and “probabilistic or”. Finally, five defuzzification methods are tested: “centroid”, “bisection of area”, “mean of maximum”, “largest of maximum” and “smallest of maximum”. All combinations lead to 2×3×5=30 experiments in total. The average waiting time per vessel was used as a criterion for choosing the best combination. The next combination of fuzzy methods gave the best result, and after the tests were performed, this combination is used in the simulations:

≠ Implication method: MINIMUM
≠ Aggregation method: MAXIMUM
≠ Defuzzification method: CENTROID

5.3. Simulation experiments

Simulation experiments were conducted for the following traffic densities: 20 (10 upstream, 10 downstream), 50 (25 upstream, 25 downstream), 100 (50 upstream, 50 downstream), 160 (80 upstream, 80 downstream), 35 (10 upstream, 25 downstream), 60 (10 upstream, 50 downstream) and 100 (10 upstream, 90 downstream) vessels per day. Traffic densities are chosen to cover wide range of densities (from 20 to 160 vessels per day) and to cover both equal (first four) and unequal (last three) distribution of arrivals from opposite directions. Simulations were conducted with a database of vessel arrivals created using statistical data with stochastic alternations. The simulations are performed over a 24-hour time period (1440 minutes). The vessel's arrival time can be obtained by knowing the speed of the vessel and its current position (the distance from the entry into the section). This information will be available through AIS system. All the simulations performed were repeated 3 times for each set individually, and the mean value was obtained.

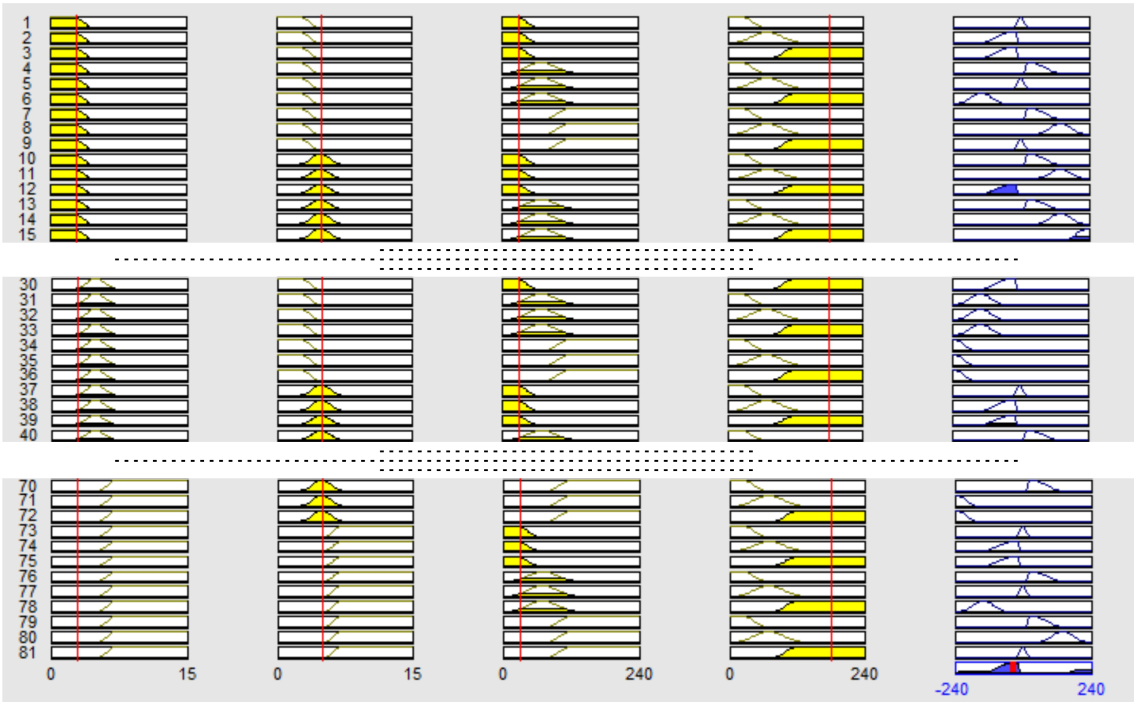

Fig. 5. Rule view – graphical representation

5.4. Results and discussion

This chapter presents the results obtained by a series of simulations, and the results of the simulations are presented in Fig. 6.

The simulation results completely confirm the basic hypothesis of the research - the possibility and necessity of adaptive vessel traffic control. Duration of the green light depends on the vessel traffic density and estimated arrival time of vessels from both directions. Shapes of signal schemes presented in Fig. 6 show that developed FCS has a significant level of adaptability to changeable traffic conditions. When traffic densities have similar values, then durations of green lights are almost the same for both directions. However, when one direction has higher traffic density, FCS reacts correctly and prolongs duration of green light for more loaded direction. Simultaneously, FCS shortens duration of green light for the direction with lower traffic density. The durations of the green lights are not constant because the vessel flows are a random variables with an exponential distribution of time between arrivals.

6. CONCLUSION

This paper presents the research on applying fuzzy control algorithm to control and improve the vessel traffic in one-way sections on inland waterways. The purpose of presented intelligent traffic light system is to replace the classical fixed (predefined) plan of traffic lights where it is applicable with the aim of waterway capacity improvement and reducing the delays. The main conclusion is that fuzzy set theory and fuzzy logic can be used to define and form the control model of the vessel traffic process. Based on fuzzy inference system, it controls the traffic lights with the goal to maximize the waterway capacity, i.e. to decrease the average waiting time per vessel. In distinction from precisely defined duration of signal plan periods, FCS introduces bigger flexibility and adaptability to exploitation conditions.

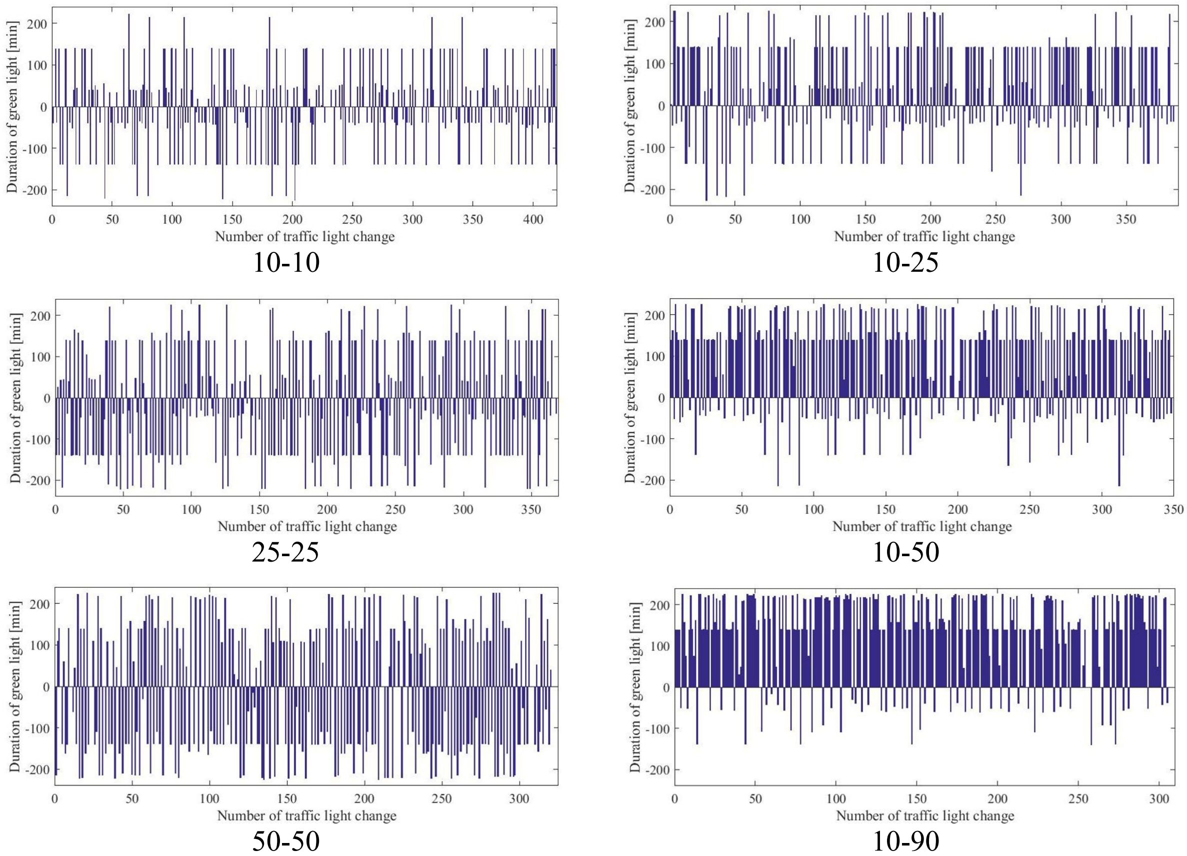

Fig. 6. Durations of green light for different traffic densities

The presented new approach in the field of inland waterway traffic control represents a rare application of artificial intelligence in water transport. Two important characteristics of the proposed system are adaptability and flexibility. It can be adapted to various lengths of one-way sections and to large spectrum of traffic densities. However, this system is designed to manage dispatching of vessels on just one narrow waterway section as an independent part of transport route.

The obtained results depend largely on the traffic density and on the length of one-way sections. Future experiments will address to the various section lengths and vessel traffic management schemes. In addition, further research may require more input variables and/or more complex fuzzy rules and possibly optimization of FCS parameters. Introducing vessel priorities (military, commercial, etc.) would also greatly contribute to the improvement of the proposed system.

Results obtained in this research can be a good foundation for the analysis of the economic viability of constructing bidirectional sections of navigable canals or design improvement of one-way canal sections [28, 29].

Acknowledgements

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