AN UPDATED FRAMEWORK FOR DIMENSIONING SAFE PARAMETERS OF INLAND WATERWAYS ADOPTING FUZZY LOGIC

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Abstract: Recently established guidelines by World Association for Waterborne Transport Infrastructure (PIANC) for designing the dimensions of the inland waterway, offer a methodology for determining safe width of inland waterways based on a concept of *safety and ease of navigation*. Therein a wide set of external and internal factors of various origin (organizational, technical, related to human) known to affect the safety and ease (S&E) of navigation are accounted for. Based on their anticipated effect, either positive or negative on S&E the labels are assigned to each factor, aggregated, and resulting effect is determined. Based on the effect, the width of the waterway is estimated. The anticipated effect of each factor is expressed in a binary manner, where the factor may improve or deteriorate the S&E of navigation, however, the magnitude of this influence is not accounted for, which we found as the main gap in knowledge. Therefore, in this paper, we introduce an updated framework for determining the S&E of navigation by improving the existing model structure and its parameters through the application of fuzzy logic. The latter is employed since waterways in each region are characterized by a specific set of factors, and some of them are difficult to quantify unambiguously. The information required to feed the updated model was collected through a survey employing a group of experts comprising inland ship captains, and engineers, with at least 3 years of work experience. The proposed concretization of the influence of factors on the resulting assessment will improve the design of the dimensions of the inland waterway. Such result assessment is the main advantage of the updated framework compared to the current PIANC management. The existing vague binary S&E estimate of inland waterways is transformed to specific values by the updated framework. The initial evaluation range [-1; + 1] remains unchanged. It is possible by approximating the incoming values of the vaguely quantified parameters into a concretized intermediate estimate value due to fuzzy logic. Therefore, the updated framework enhances this particular PIANC guidelines.

Keywords: PIANC Guidelines, Inland Waterways, Safety Navigation, Ease Navigation, Fuzzy Logic.

1. INTRODUCTION

Today, the assessment of the degree of safety and ease (S&E) of navigation on inland waterways is carried out in accordance with the generally recognised instruction of the World Association for Waterborne Transport Infrastructure (PIANC) [1]. This instruction covers a number of factors that influence navigation conditions, but the extent of this influence is not accounted for. Thus the existing PIANC recommendations are binary in nature, which on one hand is convenient but on another is a limitation of the method and results obtained. This stems from the fact, that the influencing factors can either be regarded as safe and comfortable or exactly the opposite. In reality, it is not entirely correct to evaluate different conditions in the same way. Therefore, it is necessary to extend the binary representation of the S&E of the navigation assessment by using appropriate modelling techniques, for example fuzzy logic. This will improve the understanding and usability of the existing PIANC recommendations by providing a more comprehensive (non-binary) representation of the navigation condition assessment.

The feasibility of using fuzzy logic to improve the assessment of S&E of navigation on inland waterways is justified by analysing the factors used for the assessment [1]. Some of them are difficult to quantify. This leads to difficulties in establishing a pattern between the factor and the direct assessment of S&E in navigation. One of them is a group of factors related to the level of command communication on the ship. The significance of such characteristics and their ambiguous representation are discussed in the study [2]. In addition to team communication, stress resistance and the internal state of all crew members also have a significant impact on the safety of navigation. This indicator can also be attributed to unclear factors [3-4]. In addition, experts argue in their surveys that the human factors affecting safety are largely difficult to quantify. Even if there is one, such an assessment can only be considered superficial. This is also confirmed by the results of studies [5-6]. From this we can conclude that in the structure of the assessment factors proposed by the PIANC, at least one third is unclear. This creates the conditions for the use of fuzzy logic to address these challenges [7-9].

It should be noted that this is the first time that fuzzy logic has been used for S&E in inland navigation. However, there are several studies dealing with decision support systems based on fuzzy logic that affect the safety and ease of navigation. In [10], fuzzy logic is used for situation assessment. The result of the evaluation should help the skippers to ensure the safety of navigation. However, the conditions of inland navigation are not considered there. While in [11] the multi-stage assessment of inland channel safety is carried out using fuzzy logic and the deep-water channel of the Yangtze estuary as a case study. The following factors are considered there: hydrometeorological, related to channel condition, related to traffic and managerial). It is an interesting approach however the factors considered are taken on a general level.

In [12] the influence of the navigational environment on the risk of ship collisions is studied through the assessment of the safety of navigation employing fuzzy sets and fuzzy logic. Unfortunately, it is not entirely clear which navigation components are accounted for. However, the work also shows the possibility of using fuzzy logic to assess the S&E of inland navigation.

Therefore, the study aims to update the existing framework determining the S&E of navigation for inland waterways by enhancing the existing model structure and its parameters using fuzzy logic.

2. FRAMEWORK AND METHODOLOGY

Based on the aim of the study the following research questions (RQ) are formulated:

a) RQ1. How can an expert group be formed to expand the existing influencing factors and to identify additional factors for the assessment of S&E in navigation?
b)
c) RQ2. How to choose the type of membership function and fuzzy inference used to evaluate the S&E of navigation?
d) RQ3. How to validate the new navigation S&E assessment?

Mathematical interpretation of the S&E of navigation estimation problem with the help of fuzzy logic is as follows:

$$SE = f(FM_1, FM_2, + FM_n) \tag{1}$$

Where *SE* – the result of S&E of the navigation assessment using a fuzzy model *f*, which comprises a set of influencing factors (*FM*) identified by experts based on PIANC recommendations and their own experience.

An updated framework for dimensioning safe parameters of inland waterways is presented in Figure 1. This interpretation is a step-by-step explanation of how to perform an enhanced assessment of S&E of navigation using a fuzzy model. Therein an important step is to configure the fuzzy model for evaluating the S&E of navigation. This involves selection of the most suitable type of the membership functions. To this end triangular and trapezoidal functions are compared with the bell-shaped function. In the Figure 1, "unsuccessful" means that additional fuzzification is necessary. On the other hand, "success" means that we have defined the best configuration option for a fuzzy model with more precise membership functions. The highlighted types of membership functions above could be used for such a fuzzy model, so it's important to find the best option.

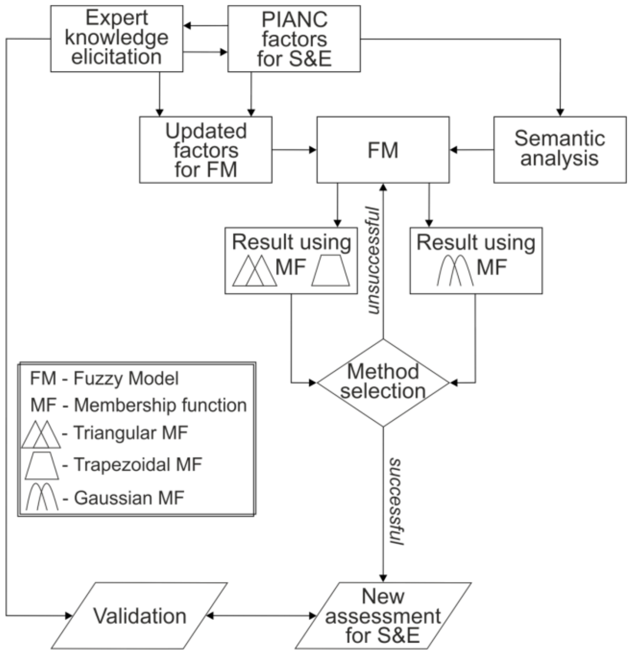

Figure 1. An updated framework for dimensioning safety parameters of inland waterways

The updated S&E assessment framework highlights several key stages:

1) Justification for the use of fuzzy logic to obtain an extended estimate. This involves analysing the factors of each group for their fuzzy characteristics.
2) Forming a group of experts and conducting a survey. The aim of this stage is to clarify the structure of each of the factors. If necessary, expand by adding a third parameter.
3) Presentation of the structure of a fuzzy model. Determine the input factors and their range.
4) Selecting the type of membership functions and the type of fuzzy inference. A justification for the choice between triangular, trapezoidal or bell-shaped membership functions.
5) Validation of the result by comparing the S&E of the inland waterways navigation assessment obtained from the fuzzy model with the current PIANC recommendations.

2.1. Data origin

The following data sources are employed in the study:

a) PIANC guidelines to obtain the type and range of factors for the S&E assessment, [1].
b) Experts knowledge on inland navigation obtained in the course of survey.
c) Experts knowledge on modelling choices specifically with respect to membership functions, i.e. emphasising the limits of the range of changes in input factors.

All types of data were used to determine the range of changes in the incoming and outgoing risk factors. The numerical values for the dimension parameters were applied to the membership functions to fuzzify them.

The immediate scheme for using factors from the first group of PIANC [1] in the construction of a fuzzy model can be seen in Figure 2. Therein separate blocks of the fuzzy model are developed for each influencing factor. In addition, each factor is defined by three parameters that enable an extended assessment of the S&E of navigation. Subsequently, each block delivers its own result, which are finally summed up yielding a comprehensive assessment of the S&E of the navigation. A brief description of the group of factors employed here, according to the current PIANC guidelines, is provided in subsection 2.2.1.

The result obtained from the updated framework feature higher granularity compared to the original version of the framework contributing to the increased understanding of the current PIANC recommendations, which only provide for a binary assessment of S&E of navigation. Since the updated five-level S&E assessment enables a more detailed approach to navigation planning on different rivers, as well as detailed assessment of different sections within the same waterway. According to experts, this can improve the ease of navigation while maintaining a sufficient level of safety for navigation.

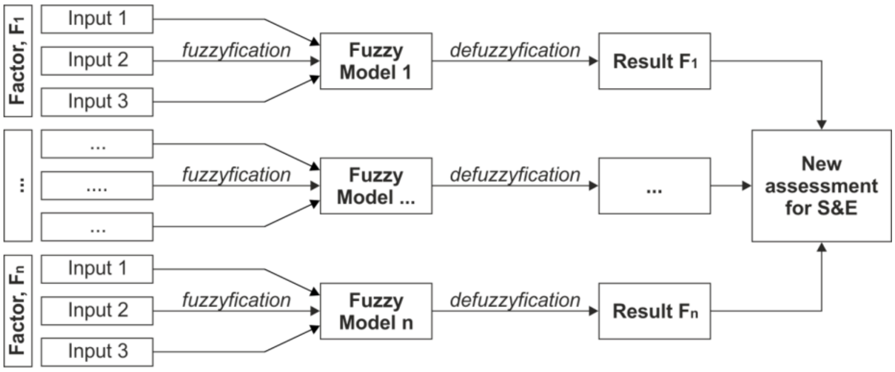

Figure 2. Fuzzy model conceptual framework

2.2. Methods

2.2.1 Brief description of factor groups for S&E by PIANC guidelines

In this subsection, brief description of the factors influencing the S&E of navigation are presented, as per PIANC guidelines [1]. The factors are divided into three group as follows:

1. Waterway-Related Criteria to Analyse or Choose Ease Categories. This group is represented by seven factors that are considered when assessing the parameters of the waterway (depth, width, etc.), as well as aspects of experience and crew consistency.
2. Criteria Related to Vessel Speed, such as the speed of the vessel and the ease of control.
3. Traffic Density Criteria which include two factors assessing traffic density and intensity, as well as maneuver complexity based on traffic jams.

A detailed comparison of the PIANC First Rating Group and the updated version based on expert knowledge elicitation is presented in subsection 2.4 (Table 1). In this study, we proposed the example of new assessment of S&E navigation only for the second factor of *Waterway-Related Criteria to Analyse or Choose Ease Categories*.

2.2.2 Methods utilized in the study

The study utilized several methods:

a) The semantic analysis of the factors presented by PIANC to determine the percentage of imprecise factors. This was an additional confirmation of the feasibility of using fuzzy logic to improve the assessment of S&E in navigation.
b) An expert survey was conducted among captains, engineers and mariners to determine the significance of each of the existing factors according to PIANC and to identify additional parameters where the assessment factor is represented by only two characteristics (binary).
c) Membership functions (MF) in trapezoidal and triangular form to describe the updated S&E of the navigation assessment factors using fuzzy logic.
d) Bell-shaped membership functions to compare and validate the results of a fuzzy model tuned based on trapezoidal and triangular MF.
e) Matlab Fuzzy Logic ToolBox for the refinement of MF using Mamdani fuzzy inference.
f) Simulink is used to collect the fuzzy model and simulate the updated estimate directly.

2.3. Justification of advisability utilizing fuzzy logic based on semantic analysis

During the initial review of the existing factors used in the PIANC recommendations for the assessment of S&E in inland waterways navigation, it was found that some factors are not clearly formulated. For instance, using phrases like "***poorly** trained pilots*" or "***low** knowledge of waterway features and infrastructure*" can lead to ambiguity because the parameters are not quantified. This lack of quantification allows for broad interpretation. Semantic analysis can be employed to identify and address such ambiguities. This resulted in requirements for the use of non-classical assessment methods based on other than probabilistic assessment principles.

To demonstrate the feasibility of using fuzzy logic in the creation of an extended assessment of S&E in navigation, a semantic analysis was carried out. This approach is fully in line with similar evidence for the use of fuzzy logic found in papers [14-16]. In our case, the semantic analysis was performed for the first group according to PIANC [1], which consists of 7 factors. The results of the analysis are shown in Figure 3.

The presented set of words (Fig. 3) which enhance one or the other factor was originally given in the PIANC recommendations. The presence of such “amplifiers” is a prerequisite for an unclear interpretation of the factor. Therefore, of the 51 parameter properties in Group 1, 19 (37.3%) are described using fuzzy categories, which suggests that the application of fuzzy logic theory to PIANC's S&E approach is advisable.

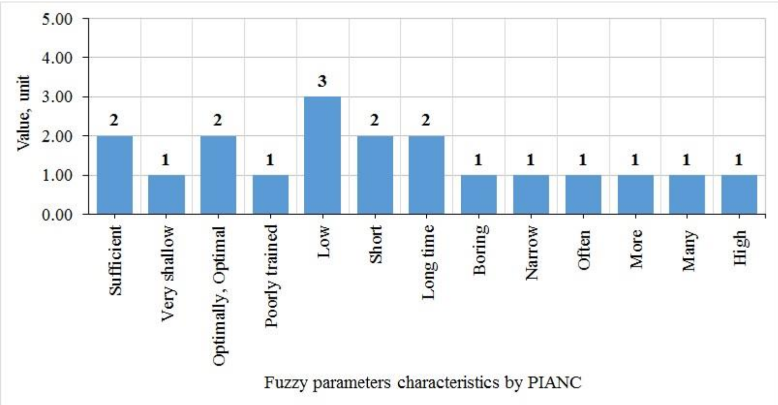

Figure 3. Semantic analysis of parameters characteristics S&E approach

2.4. Updating factors based on expert surveys

The survey was conducted from July 2023 to January 2024. A total of 10 experts were interviewed. Their professional experience ranged from 1 year to more than 10 years. Three groups of seafarers with experience in inland navigation on large rivers such as Danube (class Vb, VIb, VIc, VII), Oder (class I, II, III, IV, VIb) and Dnipro (class Va, Vb) served as experts. The composition of the experts is shown in Figure 4.

As a result of the interviews, it was found that the experts had an ambiguous understanding of some factors. This confirms the limitations in the existing assessment system by PIANC. To improve the understanding and extend the PIANC recommendations for the assessment of the S&E in inland waterways navigation, it is therefore advisable to use fuzzy logic. Following the expert survey, an updated set of factors for the first group in the assessment of the S&E of inland waterway navigation based on fuzzy logic is presented in the Table 1. This set differs somewhat from the existing one. Third parameters were added to factors that had only a binary representation. The existing set of parameters for each factor has been revised. With the help of experts, the most significant ones characterising each factor were identified.

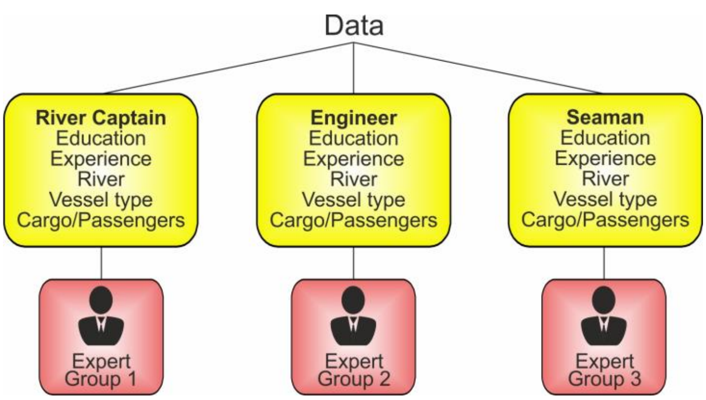

Figure 4. Expert groups

Table 1. Factors due to PIANC and expert knowledge elicitation

Factors S&E by PIANC	**Interpretation of factors parameters S&E of inland waterway navigation according to PIANC**	**Factors S&E based on fuzzy logic**	**Interpretation of factors parameters S&E of inland waterway navigation based on fuzzy logic**
Depth exploitation of waterway and type of load	Empty or ballasted vessels, no dangerous goods, sufficient water depth (+1) Deep draught vessels, especially with dangerous goods in very shallow water (-1)	Depth exploitation of waterway and type of load	Depth Vessel loading Cargo characteristics
Level of training, personnel skills and experience	Optimally qualified and experienced helmsman (+1) Poorly trained pilots, low knowledge on waterway features and infrastructure (-1)	Level of training, personnel skills and experience	Experience of the vessel's crew Knowledge of the river Crew cohesion
Attention level, distraction and stress	Short manoeuvre situation, e.g. during a meeting or by passing a bridge opening (+1) Long time or boring drive, permanent manoeuvring conditions (-1)	Attention level, distraction and stress **of the vessel crew**	River locks (number) Bridges (number) Rifles (number)
Width exploitation of waterway, danger level, possible damages	Sufficient designed fairway width, sloped banks, guiding walls, parallel dikes or short groynes besides the fairway (+1) Narrow fairway, buildings, quay walls, floating facilities, vessel berths in vicinity of the navigational area, danger of life and limb in case of accidents (-1)	Width exploitation of waterway, danger level, possible damages	Waterway (general design along the river) River banks (safe - flat dangerous - rocky) River bottom
Uncertainty of waterway conditions	Regular shoreline, sloped sand or gravel banks, predominantly low wind speed or wind protections (+1) Turbulence, secondary currents, irregular banks, long groynes, rocky or stony river bed, often wind, fog (-1)	Uncertainty of waterway conditions	Current Wind Fog
Traffic situation, interaction vessel + bank	2 or more navigational lines, accepted interaction forces (+1) One-lane traffic, many manoeuvres as overtaking (-1)	Traffic situation, **ship-ship and ship-bank-interaction**	Level of interaction "vessel-vessel" Level of interaction "vessel-river bank" Level of traffic complexity.
Vessel equipment and instrumentation	Strongly powered bow thruster or passive bow rudder, high engine power, dual propellers, optimal information systems (+1) Main rudders only or weakly powered bow thrusters, sea going ships, low engine power, no information systems (-1)	Vessel equipment and instrumentation	Engine power Manoeuvrability Information systems capability

2.5. Flowchart for the assessment of S&E of navigation by fuzzy modeling

Figure 5 shows that experts are involved in almost every stage. They identify the factors. If necessary, they extend their parameterisation. In addition, the experts are involved in clarifying the rules of the fuzzy model and carry out the final validation of the assessment results obtained. The sequence of the evaluation of S&E of navigation based on fuzzy logic is shown in Figure 5. This flowchart is universal when using the second and third group of assessment factors (subsection 2.2.1) [1]. Only the set of parameters and the possibility of additional experts change.

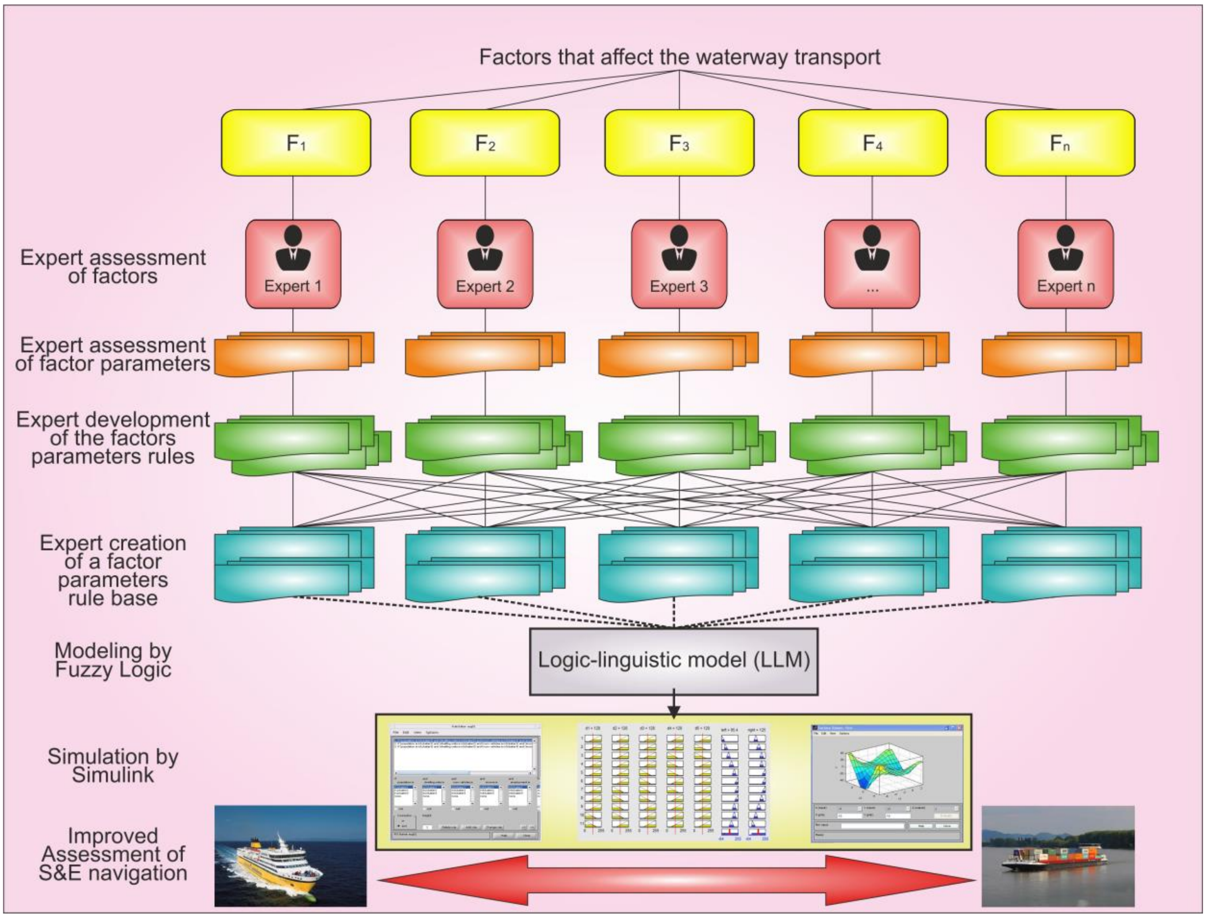

Figure 5. Flowchart for assessment S&E of navigation by fuzzy modeling

2.6. Choosing membership functions for fuzzy model

Triangular and trapezoidal membership functions are most used to solve fuzzy logic problems related to engineering, technological and economic systems [17-19]. The usefulness of this type of MF is justified by the simplicity of their fitting and the achievement of a result with minimal error. At the same time, bell-shaped, sigmoidal and Gaussian membership functions [20-22] are often used in fuzzy models. The use of the latter is due to their more flexible setting and the smoothing of the result, which may be more suitable for the assessment of S&E in navigation.

Therefore, to adjust the model objectively a two-stage approach is taken. First the triangular and trapezoidal MFs are used in the fuzzy model. Second with the bell-shaped MF is applied. The model featuring the smallest RSME (root square mean error) is selected.

2.7. Approach for result validation

To validate the results obtained, an expert evaluation in the form of tests will be carried out [23]. It is planned to carry out a validation of face, content and prognosis with the help of experts. The validation results will confirm or refute the viability of the proposed model.

Although the presented validation framework is generally not so common in engineering or technical sciences, it is quite common in the social sciences, to which risk analysis strongly tends. Therefore, the validation framework described and applied here corresponds to the state of the art in the field of risk analysis, where the results obtained, and models developed are verified by various tests. The validation process is described in detail in the study on Pitchforth's original framework [23].

It is also planned to obtain expert opinions based on the results of the comparison of the S&E of navigation assessments according to the current PIANC recommendations and obtained using fuzzy logic. At present, an experimental model has been designed to assess a single factor using fuzzy logic. Future research plans involve the development of a comprehensive model to provide an overall evaluation of safety and navigation ease, as well as a comparison of the two approaches.

3. RESULTS AND DISCUSSIONS

The expected outcome according to the updated framework for the assessment of S&E in inland waterways navigation includes the following type of assessment, as depicted in Figure 6. As an example, we show in this study how the assessment approach for the second factor of first group (*Level of training, personnel skills and experience*) described in chapter 2.4 (subsection 2.2.1) [1] would look like.

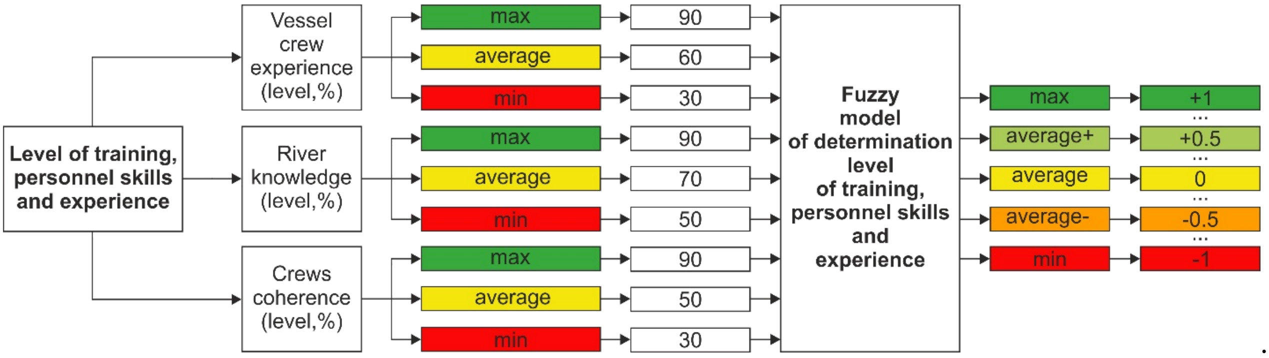

Figure 6. Example of Fuzzy model applying for assessment S&E of navigation due to second updated factor

It should be noted that the same second factor presented in “Updating factors based on expert interviews” Table 3.5 (Chapter 3.2.7) PIANC [1] is characterised by only two input parameters. These are *Poorly trained pilots*, *Low knowledge of waterway characteristics and infrastructure*, while with the help of experts, it was possible to expand this interpretation with three easily interpretable parameters: *crew experience*, *river knowledge* and *crew coherence*. According to the experts, the last parameter is important and should be specifically attributed to the second factor. Each of the parameters is characterised by three levels of change (minimum, average and maximum). The boundaries of the levels of parameter changes were defined as percentages on the basis of the survey. In result the second factor takes as an outcome five levels spanning between -1 and +1, as depicted in Figure 6. In contrast, in the PIANC guidelines this and other factors takes two values, resulting in a binary assessment of S&E of navigation [1].

Each of the five levels of the extended assessment of S&E of navigation according to the second factor can be characterised as follows:

a) **Max (+1).** Absolutely safe navigation conditions that maximise ease for the crew.
b) **Average+ (+0.5).** The navigation conditions are closed to easy but require a certain experience for safe navigation.
c) **Average (0).** The navigation on inland waterways requires due attention and extensive crew experience.
d) **Average- (-0.5).** The navigation conditions are close to difficult; the requirements for navigation experience on such rivers are high.
e) **Min (-1).** Extremely difficult navigation conditions, maximum level of training and cohesion of the vessel’s crew.

If we compare the five-level version of the assessment [-1; -0.5; 0; +0.5; +1] with the binary approach [-1; +1] according to the current PIANC recommendations, we can more precisely evaluate S&E of navigation as on river in whole and their parts. The fuzzy logic with a five-level rating allows you to move away from the unambiguous understanding of navigation conditions: either bad or good. This is correct, because under real navigation conditions it is almost impossible to characterise navigation as bad or excellent.

Based on the experts' conclusions on the second factor, which simulates the assessment according to fuzzy logic, it is concluded that it makes sense to apply this mathematical apparatus and other factors of the first group. Based on the presented updated framework for the assessment of safe parameters of inland waterways, this will be the direction of further research.

4. CONCLUSION

This article presents an updated framework for dimensioning safe parameters of inland waterways, accounting for experts' knowledge and fuzzy logic as modelling technique.
The feasibility of using fuzzy logic was justified based on a semantic analysis of the factors listed in the current PIANC recommendations. This concurs with the experts' view on the unclear nature of some factors as well as the ambiguity and inappropriateness of their interpretation. Based on that a new parameterisation of seven factors of the first group was carried out, which enables a correct application of fuzzy logic. Selection of the membership functions is made based on comparative analysis. While the results obtained with the use of extended (five-level) assessment of S&E of navigation demonstrate its applicability for waterways dimensioning in more detailed manner.
The direction for further research is to develop a full-fledged fuzzy model for the first group of factors, which consists of 7 factors. Also the work towards the development of suitable validation framework should be carried out. Lastly, the proposed approach would benefit from the involvement of wider groups of experts.

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