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ANFIS Based Model for Ship Speed Prediction

Preliminary communication

Timely and precise speed prediction for large merchant ships is exceptionally important in almost all aspects of maritime transport. This paper explores the possibility of using the Adaptive Neuro-Fuzzy Inference System (ANFIS) for creating models for speed prediction of a bulk carrier depending on external hydrometeorological disturbances, namely wind speed, significant wave height and the speed of the sea current. Using a navigational simulator, an appropriate data base concerning the effect of the wind, waves and currents on the ship speed with regard to different directions of the disturbances was formed. This base was used to create data sets for training, testing and verifying the validity of the ANFIS model. An analysis of the effect of selecting the appropriate input-output membership functions while creating the ANFIS model was also performed in order to solve the above mentioned problem. The results gained by the created model are surely promising, which opens a perspective on the implementation of the created model in certain segments of maritime affairs.

Keywords: *ANFIS model, prediction, ship speed, simulation*

Model za predviđanje brzine broda temeljen na ANFIS sustavu

Prethodno priopćenje

Pravodobno i što točnije predviđanje brzine velikih trgovačkih brodova ima iznimno važnu primjenu u gotovo svim aspektima pomorskoga prometa. U ovom radu ispitana je mogućnost korištenja adaptivnog neuroneizrazitog sustava zaključivanja, ANFIS sustava, za kreiranje modela za predviđanje brzine broda za prijevoz rasutih tereta u ovisnosti o izvanjskim hidrometeorološkim poremećajima, tj. u ovisnosti o brzini vjetra, visini valova i brzini morske struje. Pomoću navigacijskog simulatora formirana je odgovarajuća baza podataka utjecaja vjetra, valova i morskih struja na brzinu broda s obzirom na različite smjerove djelovanja poremećaja. Ta je baza iskorištena za kreiranje skupa podataka za treniranje, testiranje i verifikaciju valjanosti ANFIS modela. Također je napravljena i analiza utjecaja odabira odgovarajućih ulazno-izlaznih funkcija pripadnosti pri kreiranju ANFIS modela radi rješavanja spomenutog problema. Rezultati dobiveni kreiranim modelom svakako su obećavajući, čime se otvara perspektiva primjene kreiranog modela u određenim segmentima pomorstva.

Ključne riječi: *ANFIS model, brzina broda, predviđanje, simulacija*

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1 Introduction

Knowing ship speed is one of the most significant factors of the decision making phase in the entire chain of maritime economy. Regardless to whether that is necessary for economic-logistical reasons, such as a more precise prediction of the estimated time of arrival (ETA) to the port, or in order to increase the safety of navigation when dealing with a more precise navigation planning for a safer and more reliable collision avoidance, or because of a more precise fuel consumption calculation for a more ecologically acceptable navigation, or for completely different reasons, the fact remains that a better prediction of ship speed depending on the external disturbances has a wide range of implementation possibilities in maritime affairs.

Heretofore, this issue was approached in a mainly classical manner, i.e. in the spirit of classical marine hydrodynamics. In this manner, in [1] Journée developed one of the first mathematical models with a software support for ship speed prediction based on ship resistance e caused by bow waves. In [2], Faltinsen and others defined unintentional ship speed reduction caused by the so called “added” resistance of a ship in waves, wind and currents, as well as by a decrease in propulsion efficiency due to the impact of waves and an increase in the resistance. In [3], Guang developed a mathematical model, i.e. empirical expressions for calculating a speed loss of a bulk carrier with respect to the effect of wind and waves based on experimental measurements (5000 data from 11 voyages). The obtained expressions offer satisfying results from a state of calm sea to waves of 9 meters in height. An excellent overview of all methods for calculating the added resistance caused by the hydrometeorological effects on the ship known in that time, with special regards to wind, is provided by Wilson [4]. It should be noted that this issue is intensely explored and elaborated on even to this day. Thus, Prpić-Oršić and Faltinsen [5] analyze the methods for calculating ship speed loss with an emphasis on predicting the fuel consumption and emission of air pollutants harmful to the ecosystem, and Chuang and Steen in [6] analyze speed loss of an 8000 dwt tanker in moderate and heavy seas. The authors in [7] and [8] provide an overview of the most significant methods for added resistance estimation of today. They have been working on their development and improvement for several years.

In recent years, there have been a growing number of papers in this and similar fields that are based on artificial intelligence algorithms, and especially on artificial neural networks and fuzzy logic when dealing with issues closely connected to prediction and/or estimation, i.e. on genetic algorithms when dealing with optimization issues. Specifically, the application of the Adaptive Neuro-Fuzzy Inference System (ANFIS) in maritime affairs is getting wider. For example, the authors in [9] are implementing an ANFIS autopilot for oil carrier maneuvering, the authors in [10] use ANFIS for vertical motion modelling of fast ferries on waves, the authors in [11] facilitate ANFIS for the time series prediction of ship roll motion, and the authors in [12] have developed an ANFIS based model for predicting the squat effect in shallow water. The number of papers dealing with the implementation of ANFIS in modelling waves, wave heights, wave parameters, etc. [13] [14] [15] is also increasing. Due to the topic explored in this paper, the paper [16] in which Özger implements a model for prediction of ocean waves' energy from meteorological data based on ANFIS is particularly interesting. The paper [17] in which Rudan examines the possibilities of speed prediction of LNG and bulk carriers using a two layered feed forward neural network with an error backpropagation depending on certain external hydrometeorological disturbances in order to achieve a more precise determination of the domain crossing of ships navigating on intersecting courses is also very significant.

This paper analyzes and examines the possibility of facilitating ANFIS for reasons of a more accurate speed prediction of a bulk carrier with regard to the effect of external hydrometeorological factors, i.e. with regard to wind, waves and current effects in certain encounter angles. MathWorks MATLAB & Simulink was used as a software support.

2 Data base preparation and development

For the realization of the ANFIS model, it was necessary to ensure a certain quantity of input and output (experimental, simulated …) data that are vital for its training and testing. As it was almost impossible to acquire real measurements for all the initial hydrometeorological conditions taken into consideration while developing this model, the *Transas* navigational simulator was used as a basis for developing the needed data base. The before mentioned *Transas* Marine Navi-Trainer NTPRO 4000 simulator is installed at the *Faculty of Maritime Studies* in Rijeka with a valid certificate issued by *Det Norske Veritas – DNV*, "Class A – Standard for certification of maritime simulators No. 2.14".

As already mentioned in the introduction, the influence of the external disturbances on a bulk carrier was analyzed. From the four installed models of ships for bulk cargo transportation within the Navi-Trainer NTPRO 4000 simulator, the fully loaded ship, the basic characteristics of which are shown in Table 1 [18], was selected. In the same reference, other significant characteristics of this ship are also listed.

Concerning the external disturbances in the used navigational simulator *Transas* NTPRO 4000, wind is described as a uniform flow of air around the ship with a constant direction and speed, and all is defined at the height of 6 meters above sea level. Structural formulae for all aerodynamic hull and superstructure characteristics are defined by functions expressed by partial sums of the Fourier series [19].

Table 1 **Basic characteristics of the used fully loaded bulk carrier (*Transas* NTPRO 4000, Bulk Carrier 2)**
Tablica 1 **Osnovne karakteristike korištenog potpuno nakrcanog broda za prijevoz rasutih tereta (*Transas* NTPRO 4000, Bulk Carrier 2)**

Length Over All (LOA)	290.0 m
Breadth	46.0 m
Draft Middle in Full Load	18.1 m
Displacement	202000 t
Deadweight	179658 t
Block Coefficient	0.85
Total Rudder Area	95..1 m^2
Speed in Full Ahead	14.6 knots
Main Engine Power	14720 kW

In the used simulator, sea currents are modelled as a constant flow with a given speed distribution. Sea current speed variation connected with sea depth is not taken into consideration. Forces and moments caused by the effect of the current on the ship are defined as a sum of two components: forces and moments of the sea current in a steady constant flow, and forces and moments of the sea current caused by its irregular flow [19].

In the *Transas* NTPRO 4000 simulator, the sea state (waves) is modelled as a stationary process with spectral characteristics that correspond to the real sea waves states. For the wave energy spectral density function, a generalized Pierson-Moskowitz spectrum [20] [21] is used with the parameters of which adapt to the navigation area selection [19]. A 3D polyharmonic irregular wave model is used with the sea state described by the significant wave height $H_{1/3}$, and the general sea direction φ_{WV}. The surface of the waves is defined as the sum of harmonics [19] [23]:

$$\begin{aligned}\zeta(x_g, y_g, t) &= \sum_{i=1}^{N} \zeta_i(x, y, t) = \\ &= \sum_{i=1}^{N} A_i \cdot \cos\ [k_i(x\cos\mu + y\sin\mu) - \omega_i t + \varepsilon_i]\end{aligned} \tag{1}$$

with ζ being wave surface ordinate (z-coordinate), i – the ordinal number of the harmonics, N – the total number of the harmonics, A_i – the amplitude of the i-th harmonic, k_i – the wave number, μ – angle of wave propagation relative to ship's heading, ω_i – the frequency of the i-th harmonic, ε_i – the phase of the i-th harmonic, x_g and y_g – coordinate axes of the motion plane. Because of the particularities of the sea roughness, the model used on the simulator consists of N = 20 harmonics. On the simulator, the effect of the waves on the ship is defined by calculating longitudinal, lateral and vertical forces, and roll, trim and yaw moments. A very detailed analysis of the effect of the wind, sea currents and waves on a ship was also performed by Fossen [20].

The simulations of various hydrometeorological effects on the ship speed were performed with certain limitations. All the values are simulated so that all the external disturbances come from the same direction, which assumes that the waves are formed as wind waves and that the sea currents are generated by wind. The initial course of the ship in each simulation was 0° (N), and the direction of the external disturbances varies. It was assumed that the ship retains its given course regardless of the external disturbances, thus the ship's autopilot option for tracking the planned voyage (*Tracking control* or *Tracking mode*) was used. With the final determination of the ship speed, the ship speed over the sea bed was taken into consideration, i.e. the ship speed with respect to the sea bed which is gained as a resultant of the speed through the water and the effect of the sea current, wind and waves on the ship. All the simulations were performed on the sea area of great depths (over 100 m), and it can be assumed that sea depth has no significant effect on the ship speeds that are taken into consideration. In all the simulations, the basic assumption was that the ship constantly navigates at full speed ahead (v), which is a common speed in commercial navigation.

In the analyzed simulation scenarios, a bulk carrier sailed from the port of Rijeka towards the exit of the Adriatic Sea (the open part of the Adriatic Sea, away from the coast). Thus, the initial values of the predefined hydrometeorological scenarios (*wind, waves, current*) were selected by varying their values from the following sets:

wind – simulated wind speed: {0, 10, 20, 30, 40} (knots)
waves – simulated significant wave height: {0, 1, 2, 3, 4} (m)
current – simulated sea current speed: {0, 1, 2} (knots).

The mentioned values of wind speed, wave height and sea current speed were selected according to the Scale of Sea State for the Adriatic Sea with respect to the World Meteorological Organization (WMO) [21].

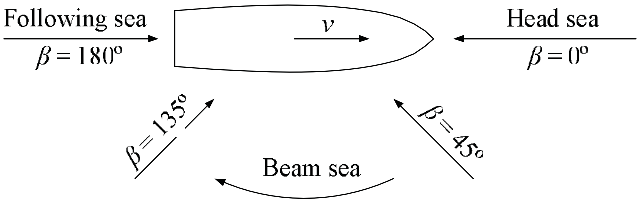
While selecting the displayed values of the wind speed and significant wave height, for which the simulations on the navigation simulator were performed, their frequency of occurrence in the Adriatic Sea was taken into consideration. As shown in [21], the wind speed of 40 knots with the corresponding significant wave height of 4 m in the Adriatic Sea has a frequency of 95.8%; the values of higher wave heights were not taken into consideration while creating the ANFIS model. The defined values of sea currents were taken with regard to possible values of sea current speed caused by wind on the Adriatic Sea, where the ones in the surface layer normally do not rise above 1.5 knots [22].

Due to symmetry reasons, directions of external disturbances effect that were taken into consideration vary from 0° to 180°, and are from the following sets of encounter angles $\beta = 180 - \mu$:

$$\beta_1 \in \{0°, 45°, 90°, 135°, 180°\} \text{ i } \beta_2 \in \{22°, 67°, 112°, 157°\}.$$

It should be noted that in this paper, the recommendation of the *Society of Naval Architects and Marine Engineers (SNAME)*

Figure 1 **Encounter angles ship-disturbance for ANFIS model**
Slika 1 **Susretni kutevi brod-poremećaj za potrebe modela ANFIS**



concerning the definition of wave movement courses with respect to the ship [23] was neglected. The reasons for such action are of merely practical nature and are closely connected to the manner in which the encounter angle is defined for the wind, waves and sea current on the *Transas* navigational simulator. In other words, for reasons of the peculiarities of this paper, the encounter angle was defined as shown in Figure 1, but it is perfectly clear that even the encounter angle defined in this manner can easily be transformed and conformed to the *SNAME* recommendation.

For the values of the encounter angle β_1, only several combinations of the before mentioned values of wind speed, significant wave height and sea current were taken into consideration, because it is clear that many of them do not have physical meaning. Therefore, the combinations for wind speed and significant wave height were taken according to Table 2.

Table 2 **Combinations of wind speed and significant wave height used for developing ANFIS model**
Tablica 2 **Korištene kombinacije brzine vjetra i značajne visine vala za izradu ANFIS modela**

Wind speed (knots)	0		10		20			30			40	
Significant wave height (m)	0	1	0	1	1	2	3	2	3	4	3	4

The combinations in Table 2 were generally determined according to the already mentioned Scale of Sea State for the Adriatic Sea with respect to the WMO [21]. The only exceptions are the combinations (*wind, wave*) with the corresponding values (0 knots, 1 m) and (10 knots, 0 m) that represent swell (no wind, but present waves) and a sudden impact of wind (there is wind, but the waves have not developed yet) respectively. Twelve combinations (*wind, wave*) from (0 knots, 0 m) to (40 knots, 4 m) can easily be formed from Table 2. If those combinations are also additionally combined with the values of the sea current speed from the set {0, 1, 2} (knots), a total of 36 combinations (*wind, wave, current*) from (0 knots, 0 m, 0 knots) to (40 knots, 4 m, 2 knots) is acquired.

In this manner, 180 simulations of the effect of wind speed, significant wave height and sea current speed on the speed of bulk carrier from Table 1 are performed on the simulator for all the values of the encounter angle β_1 so that the external disturbances reach the ship in the angles from the set {0°, 45°, 90°, 135°, 180°} clockwise with respect to the ship's longitudinal axis (Figure 1).

While performing the research, it had been noticed that the ANFIS model had relatively poor prediction characteristics for heavy seas if trained only with the encounter angles from the set β_1. Therefore, the data base for ANFIS model training was additionally extended for 72 scenarios for the encounter angles from the set β_2. For the values of the encounter angle β_2, only the combinations whose values (*wind, wave, current*) vary from (20 knots, 3 m, 0 knots) to (40 knots, 4 m, 2 knots), i.e. is the combinations that represent the state of heavy seas (18 combinations), were taken into consideration. This means that a total of 252 combinations of the effect of the external disturbances on the ship speed were available for creating (training and testing) the ANFIS model.

Each of the defined scenarios was simulated within a period of 10 minutes, and the average speed of the considered ship in the simulated scenario was determined from the last 5 minutes. The readings of all the parameters were performed every 10 seconds, and the simulation itself started with the defined values of the given scenario every time.

In the end, additional 20 different scenarios were simulated, but in the manner that the values of the wind speed, significant wave height, sea current speed and encounter angles were randomly selected. Although the selection of those scenarios was random, special attention was given so that an already used scenario did not appear among the values of external disturbances, and also that the values remained within the boundaries set according to [21]. These values were used for the final verification and evaluation of the prediction possibilities of the acquired ANFIS model for every encounter angle and for every value of external disturbances shown in Table 3.

Table 3 **Simulated values of ship speed with randomly predefined external disturbances (data for validation of ANFIS model prediction possibilities)**
Tablica 3 **Simulirane vrijednosti brzine broda za prijevoz rasutih tereta u ovisnosti o slučajno odabranim vrijednostima vanjskih poremećaja (podaci za ocjenu predikcijskih mogućnosti ANFIS modela)**

Wind speed (knots)	Significant wave height (m)	Sea current speed (knots)	Encounter angle (°)	Ship speed (knots)
27	1.8	0.4	7	13.7
9	0.4	0.1	42	14.448
24	2.4	0.5	47	13.669
41	3.7	1.8	54	11.707
25	2.5	1.1	73	13.702
22	1.6	0.4	92	14.497
14	0.8	0.2	98	14.602
5	0.1	0	102	14.607
19	1.4	0.3	119	14.711
33	2.7	1.6	122	15.058
28	2.8	0.5	172	15.163
17	1.2	0.2	143	14.802
33	3.1	1.1	133	14.929
33	3.7	0.9	132	14.812
12	1.3	0.1	100	14.609
8	0.7	0.1	93	14.594
34	2.7	0.9	86	14.006
22	2.2	0.3	58	13.969
38	3.7	1.3	40	11.887
42	4.1	1.7	8	11.311

3 Adaptive Neuro-Fuzzy Inference System for ship speed prediction

The Adaptive Neuro-Fuzzy Inference System (ANFIS) presented by Jang in his paper [24] is a universal approximation system with a wide spectrum of applications. In [24], Jang described possible applications of the ANFIS architecture for modelling nonlinear functions of multiple variables, identifying nonlinear components of an on-line control system and for predicting chaotic time series. In the introduction of this paper, some significant applications of the ANFIS model in maritime affairs were cited, and in the following sections, the emphasis will be put on testing the possibilities of developing a model for ship speed prediction depending on external hydrometeorological disturbances by means of ANFIS system.

Generally speaking, ANFIS is an algorithm for automatic adjusting of the Sugeno (Takagi-Sugeno-Kang) fuzzy inference system based on the training data. The Sugeno inference system is very similar to the even better known and more often used Mamdani inference system [25]. The first two parts of the fuzzy inference process, fuzzification of the input parameters and the application of the membership functions (MF) are practically identical. The only difference is that the output membership functions of the Sugeno system can be either linear or constant.

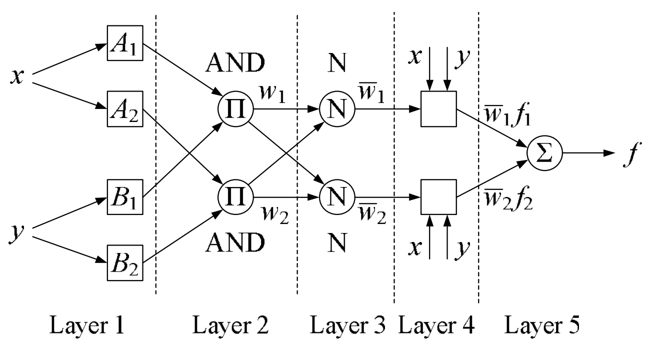
By using the input-output data set, ANFIS creates a Fuzzy Inference System (FIS). The membership functions parameters are adjusted with backpropagation learning algorithm or combined with the method of least squares (hybrid learning method). This kind of adjusting enables FIS system learning from the data used for training [25] [26].

In order to demonstrate the ANFIS architecture more easily, let us assume that the following fuzzy rules can be applied to two input parameters x and y, and one output parameter z:

Rule 1: IF x is A_1 AND y is B_1 THEN $f_1 = p_1 x + q_1 y + r_1$,
Rule 2: IF x is A_2 AND y is B_2 THEN $f_2 = p_2 x + q_2 y + r_2$,

where x and y are inputs, A_i and B_i are fuzzy sets, f_i linear input functions, p_i, q_i and r_i are parameters adjusted during the network training phase. The structure of the ANFIS network for the implementation of these two rules is shown in Figure 2 with circles and crosses representing fixed and adaptive nodes respectively.

Figure 2 **Network structure of ANFIS model**
Slika 2 **Struktura mreže modela ANFIS**



In the first layer, all the nodes are adaptive. The outputs of the first layer are inputs to which the membership functions are associated (usually two on each input), and can be expressed as:

$$O_i^1 = \mu_{A_i}(x), \quad i = 1,2 \tag{2}$$

$$O_i^1 = \mu_{B_i}(y), \quad i = 1,2 \tag{3}$$

where μ_{A_i} and μ_{B_i} can be any membership functions. For example, for a bell-shaped membership function (*gbellmf*), μ_{A_i} can be written as:

$$\mu_{A_i} = \frac{1}{1 + \left|(x - c_i)/a_i\right|^{2b_i}}, \tag{4}$$

where a_i, b_i and c_i are the so called assumed membership function parameters. In the second layer, the nodes are fixed and marked by Π for reasons of simple multiplication. The outputs of this layer are calculated in the following manner:

$$O_i^2 = w_i = \mu_{A_i}(x)\mu_{B_i}(x), \quad i = 1,2. \tag{5}$$

In the third layer, the nodes are also fixed and marked by N. The outputs of this layer represent input normalization, and are calculated as follows:

$$O_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2}, \quad i = 1,2. \tag{6}$$

In the fourth layer, the nodes are again adaptive. The outputs of this layer are acquired as the products of the normalized inputs and first-degree polynomials (for the first-order Sugeno model). In other words, it stands that:

$$O_i^4 = \bar{w}_i f_i = \bar{w}_i(p_i x + q_i y + r_i), \quad i = 1,2, \tag{7}$$

where p_i, q_i and r_i are the so called consequential parameters.

In the fifth layer, there is only one fixed node labelled with Σ in which a final output as a superposition of all input signals is calculated. In other words, the total output is calculated as:

$$O_i^5 = \sum_{i=1}^{2} \bar{w}_i f_i = \frac{\sum_{i=1}^{2} w_i f_i}{w_1 + w_2}. \tag{8}$$

The goal of training (learning) is to obtain the least difference between the real and predicted values by adjusting the assumed (Layer 1) and the consequential (Layer 2) parameters.

The learning algorithm adjusts the parameters $\{a_i,b_i,c_i\}$ and $\{p_i,q_i,r_i\}$ in order to determine the optimum between the ANFIS output and the training output. When the assumed parameters $\{a_i,b_i,c_i\}$ are determined, the ANFIS output model can be written as:

$$f = \frac{w_1}{w_1 + w_2} f_1 + \frac{w_2}{w_1 + w_2} f_2, \text{ i.e.} \tag{9}$$

$$f = (\bar{w}_1 x)p_1 + (\bar{w}_1 y)q_1 + (\bar{w}_1)r_1 + (\bar{w}_2 x)p_2 + (\bar{w}_2 y)q_2 + (\bar{w}_2)r_2, \tag{10}$$

which is a linear combination of the adjustable consequential parameters p_1, q_1, r_1, p_2, q_2 and r_2. After this phase, the optimal values of these parameters are set by the method of least squares. In order to avoid problems concerning the oversized area for results searching or slow converging when the assumed parameters are not fixed, a hybrid learning algorithm that combines the method of least squares with the backpropagation learning algorithm is used. Once the optimal values of consequential parameters are set by the method of least squares, the assumed parameters adjustment is performed by the gradient descent method. Finally, the ANFIS output is calculated by means of consequential parameters. The residuals between the calculated ANFIS output values and the real outputs are used to adjust the assumed parameters for the next epoch based on the standard learning algorithm with error backpropagation.

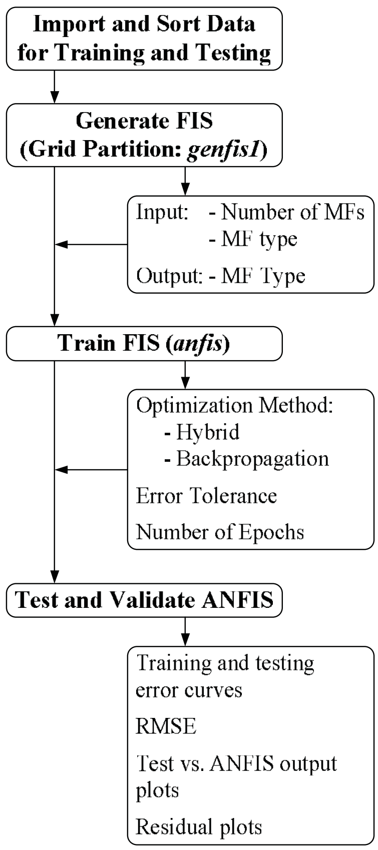
ANFIS is exquisitely implemented and supported within the MATLAB & Simulink software package [26]. The eight input and two output membership functions are at the user's disposal. Input membership functions with brief description are specified in Table 4, while the mathematical expressions with further details on these functions can be found in [26]. Output membership functions can be either linear or constant [26].

Table 4 **Overview of available input membership functions in MATLAB for ANFIS modelling**
Tablica 4 **Pregled raspoloživih ulaznih funkcija pripadnosti (MF) ANFIS modela unutar MATLAB-a**

MATLAB Command	Brief Description
dsigmf	Built-in MF composed of difference between two sigmoidal MFs
gauss2mf	Gaussian combination MF
gaussmf	Gaussian curve built-in MF
gbellmf	Generalized bell-shaped built-in MF
pimf	Π-shaped built-in MF
psigmf	Built-in MF composed of product of two sigmoidally shaped MFs
trapmf	Trapezoidal-shaped built-in MF
trimf	Triangular-shaped built-in MF

Regardless of whether ANFIS Editor, Command Window or *m*-scripts are used, data processing within the ANFIS architecture mainly remains the same, and it is shown in Figure 3.

Figure 3 **Data flow and processing in ANFIS model**
Slika 3 **Tijek obrade podataka u ANFIS modelu**



4 Application, results and analysis

In order to create and test the ANFIS model described in the previous section adequately, it is needful to classify the obtained data described in the second section. From the total of 252 simulated scenarios of the effect of the external disturbances on the speed of the bulk carrier, a matrix **M** of the 252x5 format was formed first. The rows of that matrix represent the values of the arranged 5-tuple (*wind speed, significant wave height, current speed, encounter angle, ship speed*) of the corresponding simulated scenarios. To ensure the objectivity in selecting the data set for training and testing, rows of the matrix **M** are permuted randomly, by which a new matrix $\mathbf{M_p}$ was obtained using the following Matlab code:

```
M=xlsread('C:\...\M.xls');
[numRows, numCols] = size(M);
indices = randperm(numRows);
Mp = M(indices, :);
```

out of which training samples were taken as the odd rows of the matrix $\mathbf{M_p}$ and testing samples were taken as even rows of the matrix $\mathbf{M_p}$.

During the initial testing phase, all the combinatorial ship speed interdependences with respect to the external disturbances were done. That also includes the second order combinations that provide a 3D graphical display that demonstrates the way the trained ANFIS gives a prediction for any initial requirement. The combinations that include the encounter angle alternation and any of the other disturbances are particularly interesting and are shown in Figure 4. The obtained responses from Figure 4 are not to be taken without precaution being that the dependence of the ship speed is modelled with only two external disturbances, and also because ANFIS can sometimes offer dependence without a real physical meaning in the marginal parts of the surfaces. In order to avoid such problems the ANFIS could be trained with data that exceed taken values of wind speed, significant wave height and current speed, but that assumption surpasses restrictions taken before in Part 2.

Typically, all three disturbances have the same trend when dealing with decreasing ship speed. Ship speed decreases with an increase in an external disturbance and a simultaneous turning of the encounter angle from the stern towards the bow. On the other hand, the increase in the ship speed due to the effect of the external hydrometeorological elements has somewhat different trends. Thus, in case of wind and waves, this trend is dependent almost entirely upon the encounter angle, and in case of sea current, it is equally dependent upon the encounter angle as it is on the sea current speed.

After the initial testing phase, it was confirmed that there is no need to use more than 60 epochs, and it was analyzed how the selection of different membership functions influences the quality of the response of the created ANFIS model. For validity assessment of the ship speed prediction model under the influence of external disturbances, root mean squared error (*rmse*) between the expected and the estimated values of the ship speed was used as a goal function and was calculated by the expression (11) [27]:

$$rmse = \frac{1}{N}\sqrt{\sum_{k=1}^{N}[n(k)-\hat{n}(k)]^2} \tag{11}$$

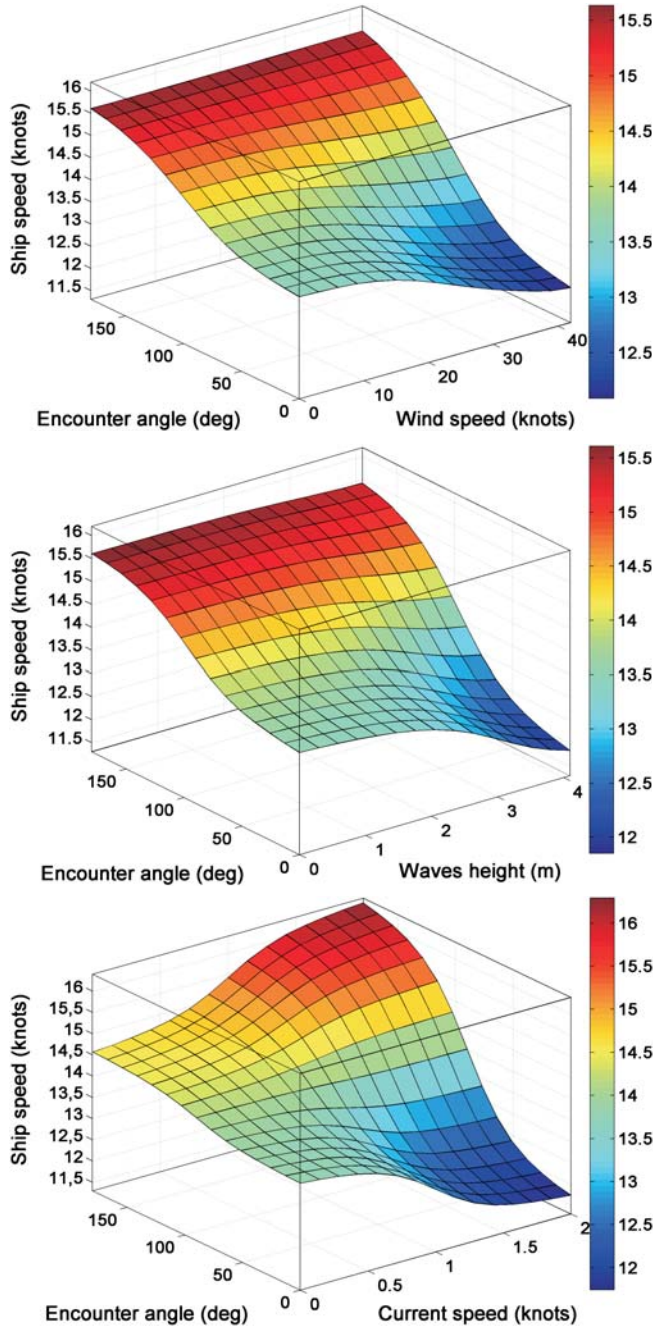


Figure 4 **Representation of the effect of analyzed external disturbances on ship speed according to the change in the encounter angle**
(a) Effect of wind speed with change in the encounter angle
(b) Effect of significant wave height with change in the encounter angle
(c) Effect of sea current speed with change in the encounter angle

Slika 4 **Prikaz utjecaja analiziranih vanjskih poremećaja na brzinu broda s obzirom na promjenu susretnog kuta**
(a) Utjecaj brzine vjetra na brzinu broda uz promjenu susretnog kuta
(b) Utjecaj značajne visine vala na brzinu broda uz promjenu susretnog kuta
(c) Utjecaj brzine morske struje na brzinu broda uz promjenu susretnog kuta

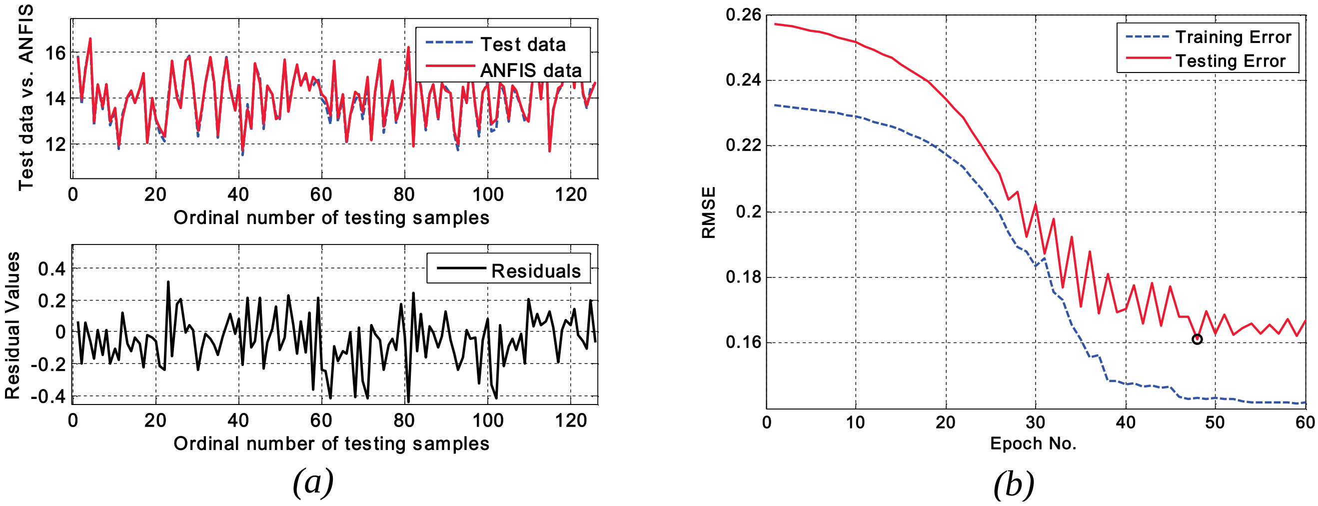
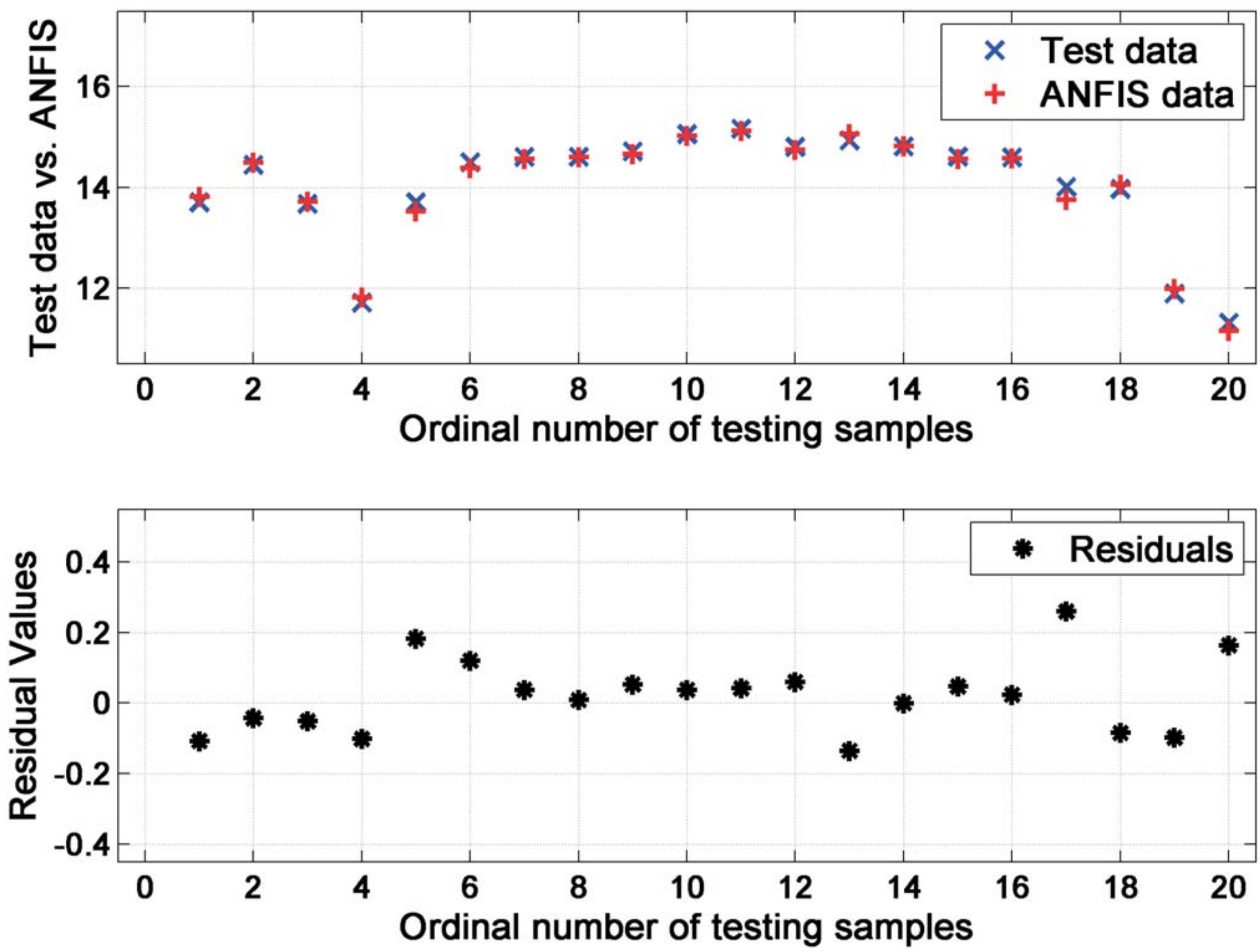


Figure 5 *(a)* **Test values of the ship speed and those obtained by ANFIS with the corresponding residual diagram (126 scenarios for training and 126 scenarios for testing);** ***(b)*** **Error curves while training and testing**

Slika 5 *(a)* **Odnos testnih i ANFIS-om dobivenih vrijednosti brzine broda uz pripadni rezidualni dijagram (126 scenarija za treniranje i 126 scenarija za testiranje);** ***(b)*** **Krivulje pogrešaka pri treniranju i testiranju**

Figure 6 *(a)* **Test values of the ship speed and those obtained by ANFIS with the corresponding residual diagram (126 scenarios for training and 20 completely new different scenarios for testing);** ***(b)*** **Error curves while training and testing**

Slika 6 *(a)* **Odnos testnih i ANFIS modelom dobivenih vrijednosti brzine broda uz pripadni rezidualni dijagram (126 scenarija za treniranje i 20 potpuno novih scenarija za testiranje);** ***b)*** **Krivulje pogrešaka pri treniranju i testiranju**



where N is the total number of the discrete values, $n(k)$ is the expected value, $\hat{n}(k)$ is the value estimated by the model prediction.

The obtained results with respect to the selected performance measure for all possible combinations of input-output membership functions are listed in Table 5.

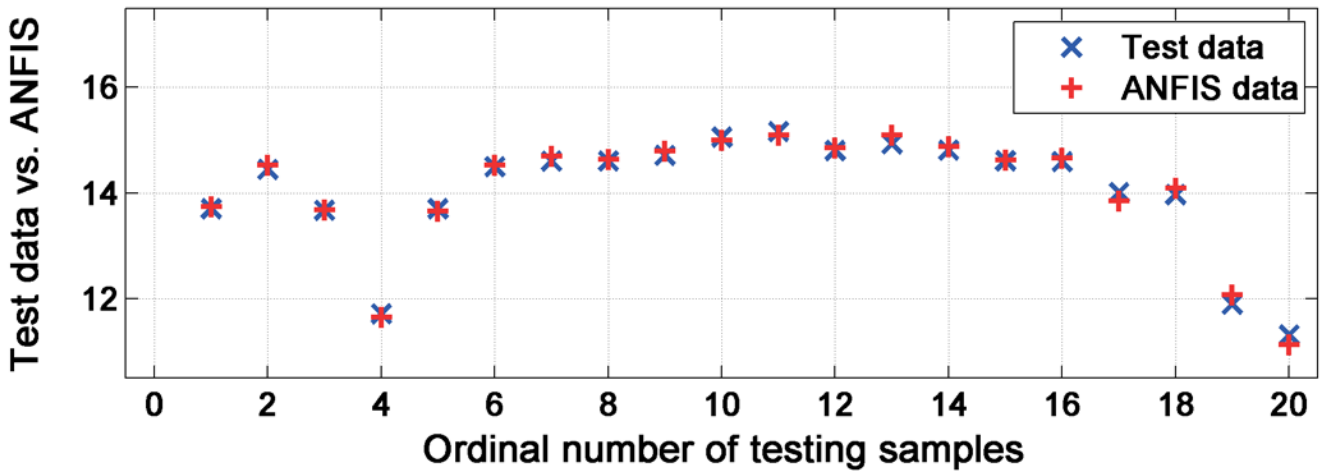
The best result of the 126 scenarios used for training and 126 scenarios used for testing was obtained using the bell-shaped input membership function (*gbellmf*) and the constant as the output membership function (*rmse* = 0.161). The response of that ANFIS model is shown in Figures 5*(a)* and 5*(b)*.

If the previously created ANFIS model based on 126 scenarios is used for predicting ship speed in cases that significantly differ from those with which it was trained, i.e. if a validation is performed using 20 considerably different hydrometeorological scenarios from Table 3, an exceptionally good response (*rmse* = 0.104), shown in Figure 6, is achieved.

How well the ANFIS model is trained, by using 126 scenarios and the above mentioned training process, can be best seen from the following fact; if matrixes $\mathbf{M}_{\mathbf{ptrain}}$ and $\mathbf{M}_{\mathbf{ptest}}$ are merged into one large 252x5 matrix $\mathbf{M}_{\mathbf{all}}$ and an enhanced ANFIS model is created with those 252 scenarios and tested only with the data from Table 3, i.e. with 20 very different scenarios, for the same selection of the input and the output membership functions, the response is only slightly better (*rmse* = 0.101) than the one from Figure 6. A somewhat better response (*rmse* = 0.097) would be achieved if a linear function is chosen for an output membership function instead of a constant. That response is shown in Figure 7, and the rest of the responses with respect to the remaining combinations of the input-output membership functions of the ANFIS model created in this manner are presented in Table 5.

Figure 7 ***(a)* Test values of the ship speed and those obtained by ANFIS with the corresponding residual diagram (252 scenarios for training and 20 new different scenarios for testing); *(b)* Error curves while training and testing**

Slika 7 ***(a)* Odnos testnih i ANFIS-om dobivenih vrijednosti brzine broda uz pripadni rezidualni dijagram (prošireni ANFIS model sa 252 scenarija za treniranje i 20 novih scenarija za testiranje); (*b)* Krivulje pogrešaka pri treniranju i testiranju**



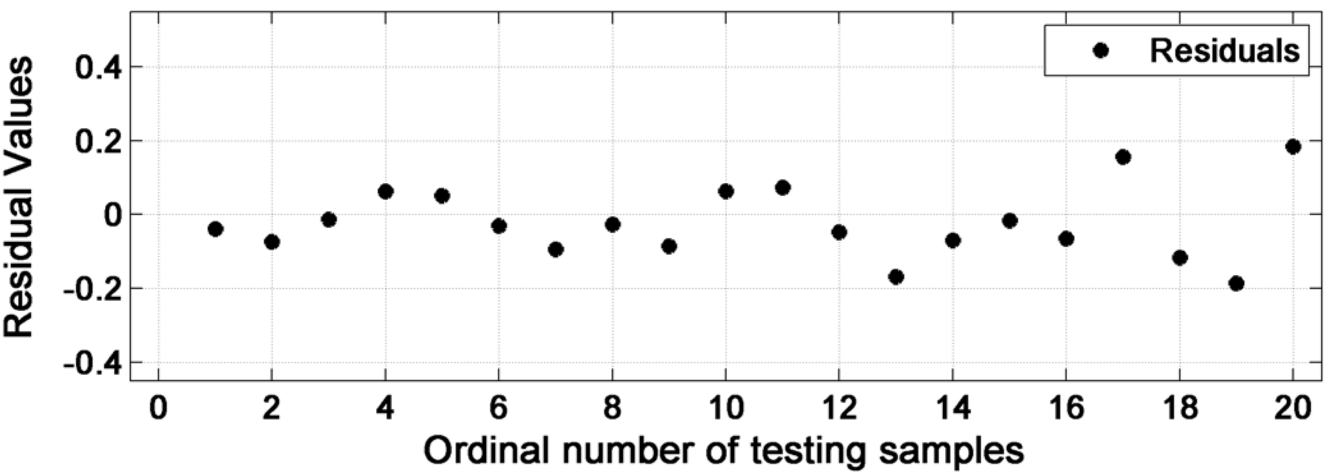


Table 5 **Review of the performance of particular ANFIS models according to the *rmse,* with respect to the selection of input-output membership functions and to different scenario selections used for training and testing**

Tablica 5 **Prikaz uspješnosti pojedinih ANFIS modela prema *rmse* s obzirom na izbor ulazno-izlaznih funkcija pripadnosti i s obzirom na različiti odabir scenarija korištenih za treniranje i testiranje**

		***rmse* values**					
		ANFIS based on 126 scenarios – Tested on 126 similar scenarios		ANFIS based on 126 scenarios – Tested on 20 different scenarios		ANFIS based on 252 scenarios – Tested on 20 different scenarios	
		OUTPUT MF TYPE		**OUTPUT MF TYPE**		**OUTPUT MF TYPE**	
		Constant	**Linear**	**Constant**	**Linear**	**Constant**	**Linear**
INPUT MF TYPE	**dsigmf**	0.287	0.162	0.243	1.530	0.252	1.576
	gauss2mf	0.314	0.201	0.257	0.692	0.146	0.145
	gaussmf	0.189	0.177	0.127	0.324	0.139	0.290
	gbellmf	0.161	0.170	0.104	0.254	0.101	0.097
	pimf	0.412	0.223	0.410	0.747	0.379	1.165
	psigmf	0.287	0.162	0.243	1.530	0.252	1.576
	trapmf	0.351	0.197	0.321	0.252	0.296	0.489
	trimf	0.294	0.303	0.235	0.229	0.232	0.234

To conclude, according to the least *rmse* from Table 5 it is very obvious that the best ANFIS model is the one using two bell-shaped membership functions per each input and a constant for the output membership function. It is especially notable that the model created using only 126 hydrometeorological scenarios provides exceptionally good results, which ensures the simplicity of the model that gives a solution to a very complicated problem of ship speed prediction in navigation under various hydrometeorological conditions often unpredictable in practice.

5 Conclusion

Although various classical methods for ship speed prediction already exist, the possibility of application of a new ANFIS based approach was tested and shown in this paper. The obtained results point to exceptionally good prediction possibilities of models created in this manner, which could result in a wide variety of practical applications such as increasing the accuracy of the estimation of ETA, a more reliable logistical planning of port and other resources (pilots, tugboats, operational quays, agents, forwarding agents...), VTS system improvement (ship position prediction), etc.

Concerning the recommendations for further research, the need for the model's generalization to a greater number of different types and dimensions of merchant ships should be emphasized as well as the option to go beyond the framework of the Adriatic Sea when selecting the hydrometeorological scenarios. Furthermore, the possibility of measuring the real hydrometeorological data on such ships simultaneously analyzing their effect on the speed should be realized. That would provide the best possible data base for creating a real ANFIS model for speed prediction of a ship that navigates through various seaways and under very different conditions and states of the sea.

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