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Ship Manoeuvring in Restricted Areas: An Attempt to Quantify Dangerous Situations Using a Probabilistic-Fuzzy Method

Lucjan Gucma, Zbigniew Pietrzykowski

(*Maritime University of Szczecin*)
(Email: lucek@am.szczecin.pl)

This paper presents a practical application of the probabilistic-fuzzy method for assessment of the safety of a ship manoeuvring in waterways. The method, based on probabilistic risk analysis and elements of fuzzy logic, takes into account situations of threatened navigational safety and situations when a navigator intuitively thinks that the safety of manoeuvring ship is threatened. The probability of grounding a ship manoeuvring in a waterway bend is determined by means of simulation method. Then, with the use of experts' knowledge and tools of fuzzy logic the probability of a dangerous situation is determined. Two different approaches are applied for the determination of that probability. The results are compared.

KEY WORDS

1. Human Factor. 2. Dangerous Situation. 3. Manoeuvring. 4. Fuzzy Probability.

1. INTRODUCTION.

Navigational safety of a ship manoeuvring in restricted areas such as waterways, harbour entrances, harbour basins, turning basins and others, is most frequently assessed by quantitative analysis methods based on probabilistic methods. One typical approach in such cases utilises data from simulated passages conducted by navigators. From the data one can estimate parameters of the density distribution function of the random variable of the distance from waterway border. The use of the density function makes it possible to determine the probability that a ship will move outside safe boundaries of the waterway, in which case a ship may run aground or strike a port structure. Such an event results in the system state being changed to safety failure and a navigational accident.

One shortcoming of the probabilistic method is that it is impossible to assess a situation when no accident occurs but safety is threatened, that is a situation when a ship is manoeuvring too close to the waterway boundary. From the safety point of view, if no or inadequate measures are undertaken, this state can result in navigational accident.

This paper presents the practical application of two different methods to determine the probability of a dangerous situation for a ship manoeuvring in a waterway bend.

The results have been compared and extensively discussed in view of their practical application.

2. THE PROBABILISTIC METHOD TO ASSESS THE SAFETY OF SHIP MANOEUVRE IN A RESTRICTED AREA.

The probabilistic method to assess the safety of a manoeuvring ship consists in determining the probability of a collision of a ship in motion, understood as a ship's deviation outside a designated manoeuvring area. Depending on the area shape, a collision may result in hitting a wharf, port structure or grounding on the bottom. The determination of collision probability is based on simulated or field studies consisting of a series of trials in which navigators handle a ship through a waterway. In the trials, the waterway in question is divided into sections defined by lines perpendicular to the waterway centre line (Gucma, 1999). The trials of reliable size, guaranteeing a preset level of confidence, are followed by the estimation of distribution parameters of the function density of random variable probability: maximum distance of ship's points to the starboard and port sides from the waterway centre line, separately for particular sections.

Two random variables are determined in each of the sections: maximum distances of ship's extreme points to the starboard and port side from the waterway centre line. When the phenomenon model (type of distribution) is determined, its parameters are estimated. In order to calculate the probability of grounding, the following equations are used:

$$p(A_{ir}) = \int_{x=d\,max}^{+\infty} g_{ir}(x)d(x) \tag{1}$$

$$p(A_{il}) = \int_{x=-\infty}^{-d\,max} g_{il}(x)d(x) \tag{2}$$

where: $g_{ir}(x)$ – density function of the random variable x of the maximum distance of ship's extreme points to the starboard side from the waterway centre line in the i-th section; $g_{il}(x)$ – density function of the random variable x of the maximum distance of ship's extreme points to the port side from the waterway centre line in the i-th section; d_{max} – distance from the waterway centre to the waterway border (half of the waterway width).

When we consider separately the starboard and port border of the waterway, vectors of safety failure for the starboard $P(A_r)$ and port side $P(A_l)$ of the waterway can be written as follows:

$$P(A_r) = [p(A_{1r}),\ p(A_{2r}) \ldots p(A_{nr})] \tag{3}$$

$$P(A_l) = [p(A_{1l}),\ p(A_{2r}) \ldots p(A_{nr})] \tag{4}$$

where: $p(A_{ir})$ – navigational safety failure in the i-th section of the starboard side of the waterway; $p(A_{il})$ – navigational safety failure in the i-th section of the port side of the waterway; n – number of sections. Thus obtained vectors, with the order equal to the number of the sections represent a probability of a ship's deviation from the waterway (accident occurrence) for particular waterway sections (see Figure 1).

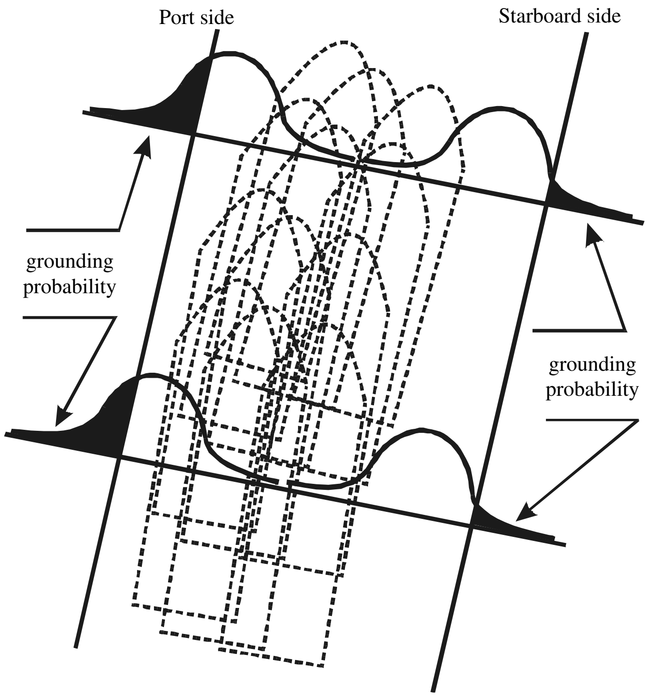

Figure 1. Probability of an accident in a waterway.

3. PROBABILITY OF A FUZZY EVENT. The approach presented above does not account for dangerous situations in which a ship comes too close to the waterway boundary; as such situations may lead to situations of safety failure. This, for instance, refers to areas difficult for navigation in which, although not many accidents have occurred, dangerous situations are observed (Driankov, 1993; Gucma and Pietrzykowski, 2001).

The probability of a fuzzy event refers to a situation when there co-exist uncertainties of fuzzy and probabilistic type. Such a case takes place when an attempt is made to determine a probability of a dangerous situation for a ship moving in a restricted area such as a waterway. A dangerous situation is meant to be a system state which, if no or inadequate countermeasures are taken, may change to the state of safety failure (navigational accident).

In the connection with the above, the term 'dangerous navigational situation' denotes the state of the ship-area system that may, but does not have to, lead to a navigational accident. Such situations are referred to as incidents. As in most cases incidents do not end in a collision, i.e. accident, they are not registered or included in any statistics. The term 'dangerous situation' is an example of a linguistic variable described by the membership function of the fuzzy set 'dangerous situation', which roughly corresponds to the fuzzy set 'dangerous distance'. An event understood as an occurrence of such situation is an example of a fuzzy event. Hence the determination of the probability that a dangerous situation will occur comes down to the determination of a probability of a fuzzy event.

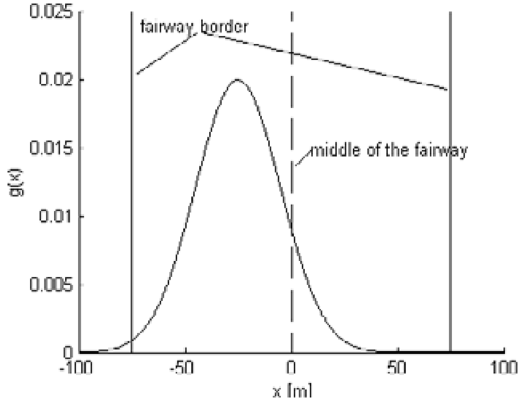

Figure 2. Density function of random variable x of the distance of the extreme point on the port side of the ship water plane to the waterway border: normal distribution, m = −25 m, σ = 20 m.

There are two basic approaches to the determination of fuzzy event probability: Zadeh's approach and Yager's approach (James, 1986; Kasprzyk, 1986). In the former the probability of a fuzzy event occurrence is a real number in the (Ayyub, 1989) interval. The latter uses a fuzzy set.

4. THE PROBABILISTIC-FUZZY METHOD OF ASSESSING A NAVIGATIONAL SITUATION IN A RESTRICTED AREA.

Two functions are essential in this task: the function of density of random variable probability and the function of membership of a fuzzy event 'dangerous situation'. Similarly to the probabilistic method, dangerous situations on the port and starboard sides of the waterway are considered separately. Therefore, there is a need to determine an appropriate function of density of the random variable x of the distance from port and starboard sides of the waterway as well as a function of membership of fuzzy sets, also for the port and starboard waterway sides (Figures 2 and 3). Using the two functions we can determine the probability of a fuzzy event 'dangerous situation'. Two approaches discussed below are used for the determination of fuzzy probability (Zadeh's and Yager's approaches).

5. RESEARCH METHODOLOGY.

The probabilistic-fuzzy method has been applied for assessment of ship manoeuvre safety. To this end both simulation research and expert studies have been performed.

5.1. *Simulation research.* The research was carried out in a waterway bend, 150 m wide at the bottom, with the radius of 600 m (Figure 4). The ship used for research was a loaded tanker with 40 000 DWT capacity, length overall L = 196 m, beam B = 28 m and draft T = 11 m. The tanker was equipped with the right-hand turn propeller and a conventional rudder (Gucma, 1999). In the studies a ship-handling simulator working in real time was used for the experiments. Ship's captains and pilots were invited to participate. The navigators were told to carry out a series of simulated passages, handling the ship through a part of the waterway. In the

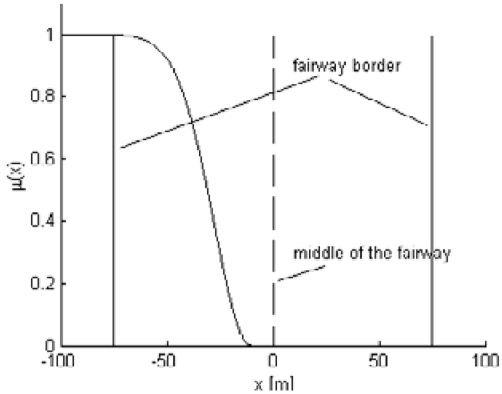

Figure 3. Function of membership to a fuzzy set 'dangerous situation' for the port side of the waterway.

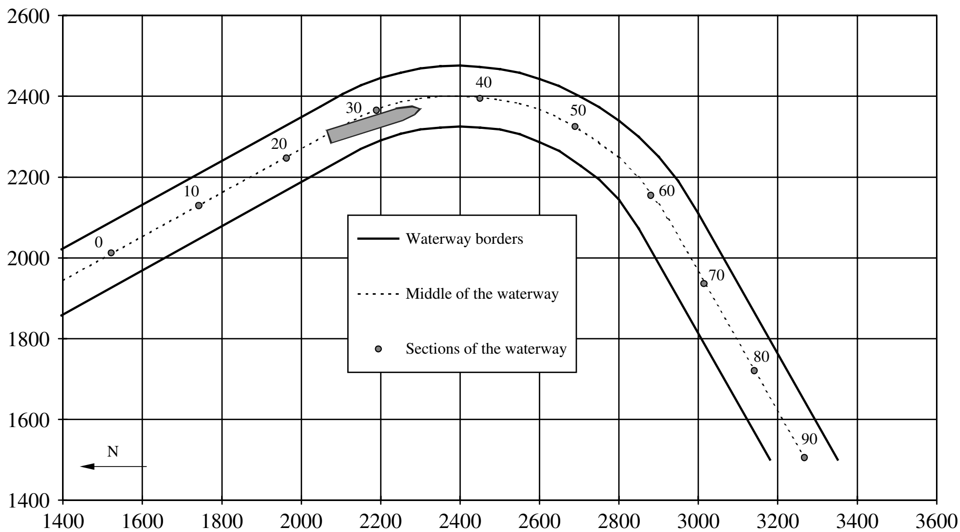

Figure 4. The navigational area of the single bend divided into sections.

manoeuvres the rudder was mainly operated. The engine was only used in particular situations, and the ship was moving at full manoeuvring speed.

After a series of simulated trials, whose reliable size (30 trials) guaranteed a preset confidence level, parameters of two density functions of the random variable were estimated: maximum distance of ship's points to the starboard and port side from the waterway centre line. The waterway was divided into sections with limits running perpendicular to its centre line. With the distance of 25 metres between sections, their total number amounted to $n=90$. Two random variables were identified in each section. It was assumed that a normal distribution describes well the distribution of ship's points to the starboard and port side of the waterway centre line, which had been confirmed by relevant statistical tests (Iribarren, 1999).

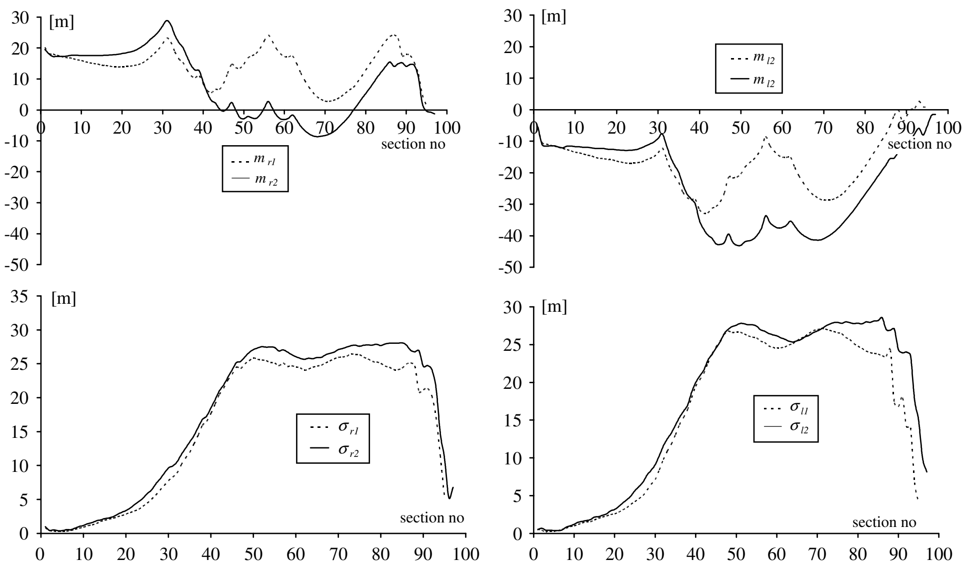

Figure 5. Estimated parameters of the mean distance and standard deviation for all sections of the waterway. Waterway starboard (right) and port (left) sides.

Two simulation scenarios have been considered: 1) zero wind condition and 2) westerly wind of 15 m/s force. Figure 5 presents the estimated parameters of the mean and standard deviation of the distance of ship's extreme points from the centre of the waterway for all the sections, their starboard (right) and port (left) sides in two simulation scenarios.

Analysing the data shown in Figure 5 we notice that the mean values of distances of ship's extreme points from the centre line of the waterway vary substantially, although the difference between the mean values needed for the determination of the safety area (so called mean swept path) does not show significant changes along the whole length of the waterway. However, there is a characteristic shift of mean values to the starboard side close to section 30, and to the port side close to sections 40 and 70 in both examined scenario's (1 and 2). This results from the character of particular manoeuvres in the bend, where in section 30 the ship moved taking a short cut due to an early turn, while in section 40 the ship moved to port as a consequence of its insufficient rate of turn; in section 70 the ship had problems with proper stopping of the turn.

An analysis of the size of standard deviations (Figure 5) shows that on the port side of the waterway higher values occur. This means that the ship's swept path will move towards the port side and the accident probability will be higher. The standard deviation of ships positions is generally higher in W 15 m/s wind scenario (2). There is a characteristic increase in standard deviations in the region of sections 50 and 70, where vital manoeuvres within the bend are to be performed (second part of the turn, turn stopping and rudder put to starboard). The swept path of the manoeuvring ship in these sections widens; consequently, accident probability increases.

5.2. *Expert studies.* The expert studies aimed to determine the membership function to a set 'dangerous situation' for the starboard and port sides of the

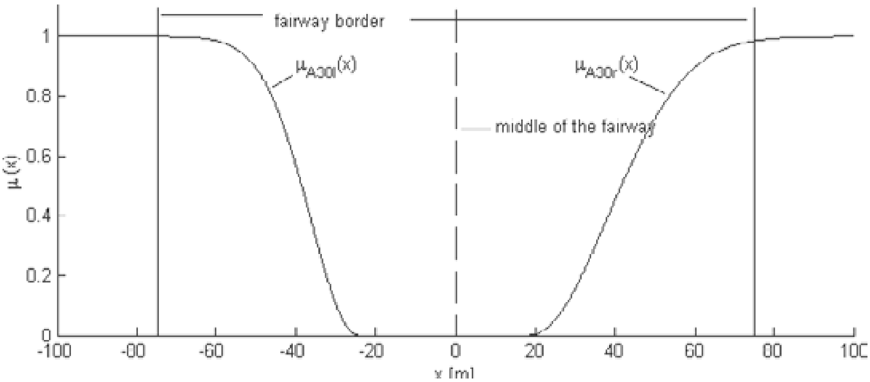

Figure 6. Membership functions to the set 'dangerous situation' for the waterway port and starboard sides in section 30.

waterway in each of the sections, $\mu_{Air}(x)$ and $\mu_{Ail}(x)$, respectively (Gucma and Pietrzykowski, 2001). The basic criterion chosen for assessing a situation was the distance of the extreme port and starboard points of the water plane from the waterway centre line. Experienced navigators who participated in the expert studies were those who had taken part in the simulated research.

Data from the questionnaires using the method of psychological scaling (Kasprzyk, 1986) was used to specify degrees of membership, found as dangerous by the navigators, to the set 'dangerous situation'. The form of the function of membership to the set 'dangerous situation' for both waterway sides, as it is known in the literature (James, 1986), was modified:

$$\begin{cases} \mu_{Air}(x) = 1 - exp(-((x - x_o)/x1)^2) & for \quad x > x_0 \\ \mu_{Air}(x) = 0 & otherwise \end{cases} \tag{5}$$

$$\begin{cases} \mu_{Ail}(x) = 1 - exp(-((x - x_o)/x1)^2) & for \quad x < x_0 \\ \mu_{Ail}(x) = 0 & otherwise \end{cases} \tag{6}$$

then its parameters (x_0 and x_1) were estimated. Examples of functions of membership to the set 'dangerous situation' for the port and starboard sides of the waterway in section 30 are illustrated in Figure 6.

On this basis the membership function parameters were estimated for the other sections of the examined waterway stretch. Their curves are shown in Figure 7. If we analyse the data shown in Figure 7 we can notice essential differences in the navigators' assessment of the degree of danger depending on a section and the side of the waterway. On both starboard and port sides of the waterway the navigator-experts considered sections 30 to 40 as the most dangerous ones. It can be seen, however, that the port side was found to be the most dangerous, where the membership function amounts to 0·9 with the distance of only 50 m from the waterway centre (more than 55 m for the starboard side). This assessment is in compliance with the theory of manoeuvring. Although on the port side the channel effect facilitates a ship's turn, there exists a serious threat that a ship will strike the port side border of the way with its stern if its rate of turn is too high. Besides, we should take into account the fact that the navigators were supposed to pass through the waterway bend, which forced

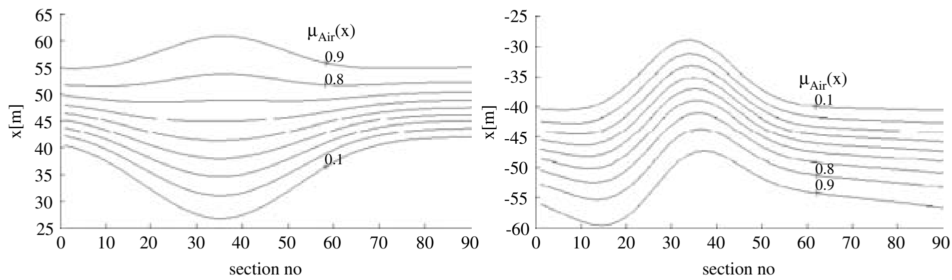

Figure 7. A level line chart of the functions of membership to the set 'dangerous situation' for the starboard (right) and port (left) sides of the waterway.

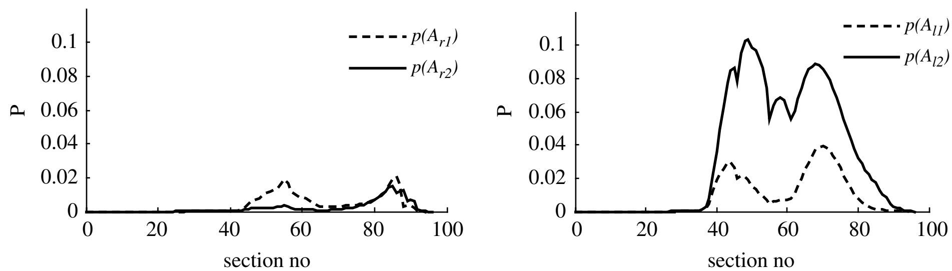

Figure 8. Probability of an accident on the starboard (right) and port (left) side of the waterway.

them to commence the manoeuvre in a strictly defined point. If the turning manoeuvre was started too early or late, its safe performance may prove impossible. The determination of the density functions of the random variable x and the function of membership to the set 'dangerous situation' made it possible to calculate vectors of probability of dangerous situation occurrence. In the calculations both Zadeh's and Yager's approaches were applied.

6. THE RESULTS.

6.1. *Accident probability*. The previously estimated distribution parameters (mean and variance) were used for determining navigational safety failure. Formulas 1 and 2 were applied to calculate the probability of an accident in given sections p_{air}, p_{ail}. The results of the calculations are given in Figure 8, which presents the probability of an accident for the entire waterway length on left and right sides for the two simulation scenarios considered (1 – no wind, 2 – westerly wind 15 m/s).

The results illustrated in Figure 8 confirm earlier analyses. It can be seen that for the first scenario the probability that a ship will go aground is visibly higher on the waterway port (left) side, while its highest values are found near sections 45 and 70 (both simulation scenarios). The highest probability of an accident on the starboard side exists in the region of sections 55 (in scenario 1 only) and 85 (both scenarios). It was found that difference between scenarios when probability of grounding is considered is much higher (double or even triple) for the port side of the waterway in W 15 m/s wind scenario (number 2). The probability of grounding on starboard side, which is the weather side for the 2nd scenario, is similar except in the first sections of the waterway.

The data presented in Figure 8 provide a conclusion that the navigators delayed the turn steering the ship too close to the port boundary of the waterway in the area of section 45. As a result, the course was corrected and, consequently, the ship was moving on the starboard side in the area of section 55. Furthermore, as a result of putting the helm to the other side, the ship dangerously moved to the port side in section 70.

6.2. *Probability of a dangerous situation – Zadeh's approach.* Assuming that we know the density distributions of random variable x for, respectively, extreme starboard ($g_r(x)$) and port ($g_l(x)$) positions of ship water plane points, as well as their corresponding functions of membership to 'dangerous situation' sets $\mu_{Ar}(x)$ and $\mu_{Al}(x)$, the probability that a dangerous situation will occur can be expressed by the equations (Gucma and Pietrzykowski 2001; Kasprzyk, 1986; Rommelfanger, 1994):

$$\mathrm{p_z}(A_\mathrm{r}) = \int_{x=-\infty}^{\infty} \mu_{Ar}(x) g_r(x) d(x) \tag{7}$$

$$p_z(A_l) = \int_{x=-\infty}^{\infty} \mu_{Al}(x) g_l(x) d(x) \tag{8}$$

Accepting the previously presented division of the waterway into sections, we can determine the probability of a dangerous situation for the starboard and port sides of the waterway in each section. As the starboard and port sides are considered separately, by analogy to relations (3) and (4), vectors of the probability that a dangerous situation will occur can be written in this form:

$$P_z(A_r) = [p_z(A_{1r}),\ p_z(A_{2r}) \ldots p_z(A_{nr})] \tag{9}$$

$$P_z(A_l) = [p_z(A_{1l}),\ p_z(A_{2l}) \ldots p_z(A_{nl})] \tag{10}$$

where: $p_z(A_{ir})$ – probability of a dangerous situation in i-th section of the starboard side of the waterway; $p_z(A_{il})$ – probability of a dangerous situation in i-th section of the port side of the waterway; n – number of sections. The values of probability of dangerous situation occurrence were defined for all the sections of the waterway on the port and starboard sides. The relevant data are presented in Figure 9.

Intuitively we may say that the probability of a dangerous situation $p_z(A)$ (Figure 9) is higher than the probability that an accident p_a occurs (Figure 8). This result from the fact that threatened safety situations were taken into account, which led to grounding avoidance (for instance, thanks to a proper response of the navigator).

An analysis of data included in Figure 9 shows that the maximum values of both functions for identifying a dangerous situation are found in places of the waterway similar to those of the function representing the probability of an accident (Figure 8). It is interesting, however, that the first maximum for the port (left) side of the waterway is located in the region of section 40 and is higher than the other maximums, which was not the case in functions describing accident probability

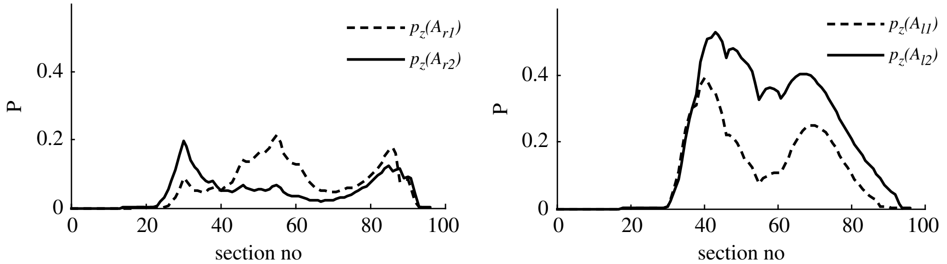

Figure 9. The values of probability of dangerous situation occurrence for the waterway starboard and port sides (Zadeh's approach).

(Figure 8). Relatively high values of the probability of dangerous situation occurrence in this part of the waterway bend may result from the fact that possible danger is vital in terms of manoeuvring tactics. Each error made when a ship enters the bend, particularly a delayed turn, causes a dangerous situation in this part of the waterway. The navigator, being too close to the port side near section 40, is forced to increase the ship's rate of turn and speed up the manoeuvre. On the other hand, when the rudder goes more to starboard, there is a threat that the ship will hit its stern against the port side slope of the waterway.

The probability that a dangerous situation will occur on the port side is lower in the area of section 70 (Figure 9) because the navigators found coming closer to the port side border as less dangerous in this part (ship leaves the bend and the section is straight) than in section 40 (curved section) in spite of the fact that the values of accident probability displayed a different trend (Figure 8). In this respect it is interesting to note the small value of the probability of a dangerous situation in section 30 on the port side as compared with the starboard side (Figure 9). Among others, this results from the fact that, although the port side is safer in navigators' opinion, (the turn is facilitated by the turning moment of the channel effect), the ship was found more frequently on the starboard side due to a natural tendency of the navigator to accelerate and take a short-cut.

The general difference between the two scenarios considered is the higher probability of dangerous situation occurrence in the second scenario except the starboard side, near section 50, where due to the difference of accident probability (Figure 8) the probabilities of dangerous situation occurrence are higher in the 1st scenario.

It is worth noting that, even if the navigator assessed a situation as dangerous, he is not able to manoeuvre the ship to avoid the danger. Consequently, in such cases the value of the probability of a dangerous situation will be high.

Zadeh's approach combines objective and subjective elements, resulting from navigators' knowledge and experience: the current situation (accident probability is the result of previous manoeuvres) and navigator's judgement concerning the degree of how dangerous is the given situation.

6.3. *Probability of a dangerous situation – Yager's approach.* With the assumption that we know the density distributions of random variable x for, respectively, extreme starboard ($g_r(x)$) and port ($g_l(x)$) positions of ship water plane points, as well as their corresponding functions of membership to the 'dangerous situation' sets

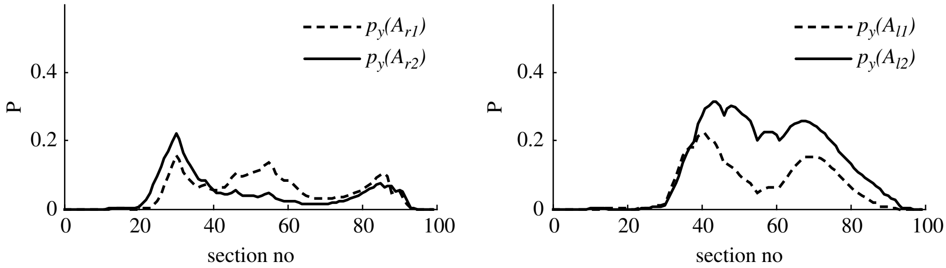

Figure 10. Probability of a dangerous situation for the port and starboard sides of the waterway (Yager's approach).

$\mu_{Ar}(x)$ and $\mu_{Al}(x)$, the probability that a dangerous situation will occur can be expressed by the equations (Kasprzyk, 1986):

$$p_y(A_r) = \sum_{\alpha\in[0,1]} \alpha / p(A_{\alpha\, r}) \tag{11}$$

$$p_y(A_l) = \sum_{\alpha\in[0,1]} \alpha / p(A_{\alpha\, l}) \tag{12}$$

where: $p_y(A_{\alpha\, r})$ – probability of a non-fuzzy event $A_{\alpha\, r}$; $p_y(A_{\alpha\, l})$ – probability of a non-fuzzy event $A_{\alpha\, l}$.

Accepting the previously presented division of the waterway into sections we can determine the probability of a dangerous situation for the starboard and port sides of the waterway in each section. To make the comparison of the results possible, only defuzzificated values of the probabilities of dangerous situations are presented.

As the starboard and port sides are considered separately, by analogy to relations (3) and (4), vectors of the probability of a dangerous situation can be written in this form:

$$P_y(A_r) = [p_y(A_{1r}),\ p_y(A_{2r}) \ldots p_y(A_{nr})] \tag{13}$$

$$\mathrm{P_y(A_l) = [p_y(A_{1l}),\ p_y(A_{2l}) \ldots p_y(A_{nl})]} \tag{14}$$

where: $p_y(A_{ir})$ – probability that a dangerous situation will occur in the i-th section of the starboard side of the waterway; $p_y(A_{il})$ – probability that a dangerous situation will occur in the i-th section of the port side of the waterway; n – number of sections.

In the next step comprising the whole waterway (all sections) the values of probabilities of dangerous situation occurring on the port and starboard sides were determined. The results are presented in Figure 10.

The comparison of data presented in Figure 10 with the values of probability obtained by Zadeh's approach shows their high similarity in terms of value and function shape. The values of probability of dangerous situation occurrence in Zadeh's approach, however, are approximately twice as high depending on the section. The fact has to be further analysed, particularly because no similar examples of application are found in the world literature (Ayyub, 1989; Kasprzyk, 1986; Rommelfanger, 1994).

It should be noted that in Yager's approach, the difference between the maximums of the function describing the probability of a dangerous situation on the waterway port side in section 40 and 70 decreased as compared with Zadeh's approach.

7. CONCLUSIONS.

The method herein described has a practical significance as it enables quantitative determination of the probability of dangerous situation occurrence. This paper presents the application of the method for determining the probability of dangerous situations as they may occur in a waterway bend where a ship is manoeuvring. Such assessment of manoeuvre safety could then be further used in the process of optimisation of the waterway shapes in view of its safety or for the assessment of the safety of a conducted manoeuvre.

The approach described in this paper has not been used in analyses so far. It combines a classical probabilistic method connected with a probability of a ship appearing in a particular position in the waterway with navigator's assessment of the degree of danger in a given place of the waterway. This assessment is described by the theory of fuzzy sets.

The paper presents a practical interpretation of the method. Two different approaches to the assessment of probability of dangerous situation occurrence (Zadeh's and Yager's) show significant similarity of results; the differences should be further analysed.

In Yager's approach, from practical point of view it is important that the probability of dangerous situation occurrence is described with a fuzzy set. In this case, methods of fuzzy logic can be used in situations where other elements are also described with fuzzy sets, e.g. safe speed.

Regardless of the above remarks, both methods allow the determination of real values of the probability of dangerous situation occurrence, which consequently provides a basis for analysis of navigational safety by conventional methods commonly used in practice.

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