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Methods for risk minimizing in the process of decision-making under uncertainty

Keywords

risk, optimization, decision process, uncertainty

Abstract

The sources of the uncertainty in the maritime transport system are described. Furthermore, the two models for human factor reliability are presented. The possibilities of mixed these two methods as the estimators for the probability of correct performance of the navigator are given. The analysis of decision-making process under uncertainty has been done. Finally, the optimization task and his possible solution are shown.

1. Introduction

Decisions at sea transport are made in a random environment it means at some uncertainty. It is the origin of certain risks involved in making decisions. The safety level in shipping is influenced by the risks resulting from the interaction of the forcing factors, affecting an elementary executive subsystem. These factors may be divided into [13]:

- *working* (within a system) – forcing factors affecting a ship as a result of realization of the shipping,
- *external* - forcing factors being characteristic for interaction of the environment affection a ship (not depending on its functioning),
- *anthrop technical* - forcing factors affecting a means of transport as a result of human actions, e.g. due to an operator's faults.

These factors can be considered separately or as the system of three categories: human errors, reliability of technical systems and environment influences, *Figure 1.*

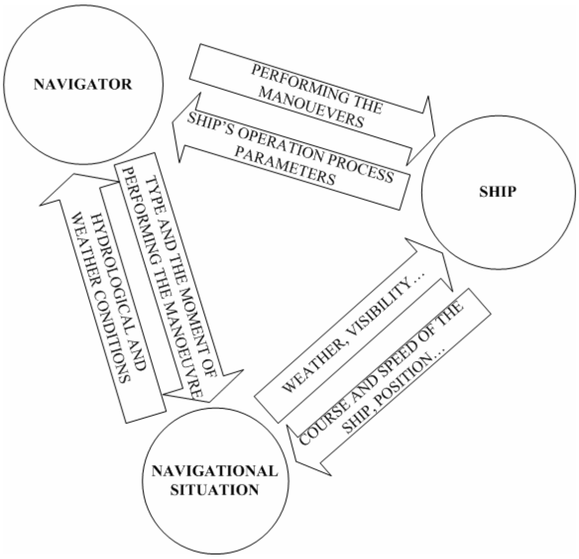

Figure 1. Triangular of relation

The shipping is a continuous decision-making process (course, speed) with the navigator as a single decedent [7] so the human factor is an important one of safety estimation in maritime transport [10], [11].
In such situation, the quality of decision-making process (especially time of making a maneuver in collision situation) has the great significance [3], [4], [8]. These depends on the navigator's experience, knowledge and acceptable level of risk, because of his decisions are based on them [3], [6]. Due to the time-varying conditions and a lack of full knowledge

of the navigational situation, navigator's decisions are taken under uncertainty [4], [6], [8]. Decisions at shipping are made at uncertainty which degree will vary from nearly relative certainty to great uncertainty. In such situation factual information could exist, but may be incomplete (the time of other ship maneuver). At decision making process the probability of an outcome can be estimate by using mathematical models or subjective probability based on judgment and experience.
The article shows the method of minimizing the collision's hazards, based on the time of decision making in situations of incomplete and uncertain information.

2. Analysis of collision risk according to human factor

There is considered the own ship and target ships in the neighborhood as the system presented in *Figure 1*. The assessment of the navigational situation is the subjective due to the navigator's relative risk attitude [3], [4]. Thus, we define the acceptable level of hazard as related to sufficient time (making and doing decisions) to avoid potential hazard situation between the own and target ships dependent on navigator's attitude.
Furthermore, we assume that:

- ***I*** – the set of own ships, ***I***={1,2,3,…, i},
- ***J*** – the set of target ships, $\boldsymbol{J} = \{1,2,3,...,j\}$, where *j* is the number of target ships on the considered area,
- ***R*** **–** the set of danger type**,** $\boldsymbol{R} = \{1,2,3,...,r\}$
- $a(i,r) \equiv a_i^r \in \Re^+$ is the number describing the *i*-th own ship's safety time needing according to collision hazard of *r*-th type,
- $b(j,r) \equiv b_j^r \in \Re^+$ is the number describing the j-th target ship's "danger supply" time of the collision hazard of r-th type,
- the $\mu : J \times R \longrightarrow \{0,1\}$ is describing the relation between the *j-th* target ships on the area and the *r-th* type of danger, $\mu(j,r) \equiv \mu_j^r = 1$ when *j-th* target ship is a risk source of *r-th* type, and the other hand $\mu_j^r = 0$;
- $M = \left[\mu_j^r\right]_{J \times R}$ – the matrix of *r-th* type of threatening objects from *j-th* target ship,
- $\Psi(j)$ - is discreet random variable describing the time for "acceptable level of hazards" (*r-th* type) and for target ship *j* with distribution function (i.e. the random variable describing the sufficient time to avoid the potential hazard situation of *r-th* type with target ship *j*):

$$P(\Psi(j) = \psi(j,l,r)) = p(j,l,r) = p_j^{l,r}, \qquad (1)$$

where

$$j \in J, l = 1,2,3,...,a(i,r), r \in R,$$

$$\underset{j \in J}{\forall} \underset{r \in R}{\forall} \; p(j,l,r) \geq 0 \text{ and}$$

$$\underset{j \in J}{\forall} \underset{r \in R}{\forall} \; \sum\nolimits_{l \subset U_j^r} p(j,l,r) = 1;$$

- $\lambda : I \times J \times R \to \Re^+$ - measure the effects of *r-th* type danger from *j-th* target ship for *i-th* own ship, where $\lambda(i,j,r) \equiv \lambda_{i,j}^r \in \Re^+$ is the number of the cost of effect, $i \in \boldsymbol{I}$**, …,**
- $g : I \times J \to \Re^+$ - significance of the effects, where $g(i,j) \equiv g_i^j \in \Re^+$ is the number describing the the strength of interaction between *i-th* own ship and *j-th* target ship,
- $x : I \times J \times R \to \Re^+$ - the measure, where $x(i,j,r) \equiv x_{i,j}^r \in \Re^+$ is describing the time to the *r-th* type risk, when the *j-th* target ship is considered, for *i*-th own ship.

2.1. Rasch model

The ship is the anthrop-technical system in which the direct realization of the tasks is dealt with by an executive subsystem consisting of navigator, steersman and a technical object (a means of transport) realizing the tasks within the system environment. In respect of a human located within a ship the significant criterion in the evaluation of the shipping is their safety. The decision making process depends of human factor because of:

- navigator's response time according to a distance of own ship to potential collision point, (analysis and issue commands),
- steersman's response time from heating to execute the command,
- subjective of navigator risk acceptance level.

The Rasch Model (RM), due to the work of Rost ([9]), contains both, latent trait and latent class variables, ([1]). We assume that the RM does not hold for the entire population of target ships, but does so within subpopulations of individuals which are not known before hand. The probability that the navigator at ship *i-th* react at collision situation with *j*-th correctly is:

$$P\left(X_{ij}=1\,|\,\theta_i,\phi_i,\beta_j\right)=\frac{\exp\left(\theta_i-\beta_{\phi_i j}\right)}{1+\exp\left(\theta_i-\beta_{\phi_i j}\right)}, \qquad (2)$$

Where

θ_i - is the *i*-th ship's ability,

φ_i - indicates which latent group of the ship *i* belongs to,

$\beta_{\varphi ji}$ - denotes the situation *j*'s difficulty which depends on group variable φ.

Suppose there are G classes, number of classes is not less than 2, the unconditional probability that the ship *i* react at collision situation *j* correctly is:

$$P\left(X_{ij}=1\,|\,\theta_i,\beta_{\phi_i j}\right)=\sum_{g=1}^{G}\pi_g\frac{\exp\left(\theta_i-\beta_{\phi_i j}\right)}{1+\exp\left(\theta_i-\beta_{\phi_i j}\right)}, \qquad (3)$$

where

- πg - probability that the ship belongs to class g,
- $\Sigma_g \pi_g=1$, and $0<\pi_g<1$,
- $\Sigma_j\beta_j=0$ or $E(\theta)=0$ for all classes.

In case of appearance the risk of collision, it is aimed to keep safety level not worse than navigator's lowest level of safety.

2.2. Human cognitive reliability method (HCR)

When the analysis of the hazard situation is concentrated at influence of human factor in decision making process, then the assessing the possibilities of navigator's errors are made by known methods. For example it can be done by HCR (Human Cognitive Reliability) [5]. The clue of the method is calculating the operator's probability of non-response to a cognitive processing task as a function of time, according to formula:

$$P(t)=\exp\left(-\frac{t/t_{0,5}-C_{e,i}}{C_{g,i}}\right)^{B_i} \qquad (4)$$

where:

t – time for perform the task (making and doing the decision),

$t_{0,5}$ – median time what to perform the task corrected by a shaping factor K_i,

B_i – shape parameter,

$C_{e,i}$,- time delay factor as fraction of $t_{0,5}$ for type *i-th* cognitive processing (skills, rules, knowledge),

$C_{g,i}$, - scale parameter as a fraction of $t_{0,5}$ for type *i-th* cognitive processing (skills, rules, knowledge).

During the analysis with HCR method, the influence of three factors important for type of cognitive processing:

- navigator's experience,
- stress level,
- ergonomic quality of steering office.

After do the assumption about the conditions, the influence of these factors is taking into account in $t_{0,5}$, according to equation:

$$t_{0,5}=t_{0,5nom}\prod_{i=1}^{3}\left(1+K_i\right), \qquad (5)$$

where

K_i - the values of the coefficients (shape parameters) are given in table 2,

$t_{0,5nom}$ - the value of the theoretical median time what to perform the task.

Table 1. Corrective coefficients (shape parameters) in HCR method [5]

Factors making the cognitive processing	***Coefficients***
Navigator's Experience:	***K1***
Expert, high skills	*-0,22*
Average knowledge and training	*0,00*
Begginer, minimal skills	*0,44*
Stress's Level:	***K2***
Extreme danger situation	*0,44*
Potential danger situation	*0,28*
Normal situation - no danger	*0,00*
low vigilance, monotone	*0,28*
Ergonomic Quality of Steering:	***K3***
excellent	*-0,22*
good	*0,00*
enough	*0,44*
bad	*0,78*
very bad	*0,92*

To simplify it can be use the plot given in *Figue 2*. The X axis is variable "Time (Normalized)", i.e. t/ $t_{0,5}$. The axis Y describes the non-response probability operator (navigator).

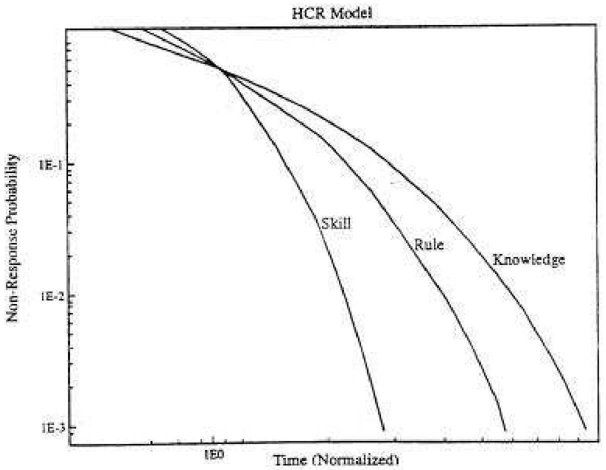

Figure. 2. Graphical representation of human reliability function according to HCR method ([4])

This method is useful when only the limits of the time interval for making and doing the decision are known. Then, the probability values, given by (2)-(3), can be estimated according to (4). Thus, the following formula is given:

$$P\left(X_{ij}=1\right)=\exp\left(-\frac{t/t_{0,5}-C_{e,i}}{C_{g,i}}\right)^{B_i} \qquad (6)$$

2.3. Decision-making process under uncertainty

The elements of intuitive assessment of the situation could be considered in term of decision-making algorithms. Fixed set of parameters that will have the greatest impact on the functioning of the system and how much, change in these parameters, affect the behavior of the system in the future.

From this perspective, the alternatives should be examined, and their selection should be made. Choosing the right solutions, in conditions of uncertainty, often conducted with the use of models to appeal to game theory [12]. In this category, the important thing in decision-making process is choosing the strategy. It is the set of all navigator's actions (participant games), which are taken by him at any stage of the game. Due to the fact that the navigator has repeatedly makes decisions [6], his conduct is determined as a mixed strategy. On the sea, the decision-making process should also consider the impact of the environment. Then the selection criteria can be divided into two groups:

I. The behavioral rules - is essential to determine possible losses and gains,
II. Group criteria optimization.

There are following rules in the first group:

- maximum from the minimum,
- regret matrix (Savage's method),

and the second group:

- Hurwicz's method,
- the expected average method.

During the ship's passage there can be following sources of uncertainty:

- no communication or agreement between the two vessels,
- lack of information about the maneuvers of the second vessel,
- no information about the weather,
- incorrect reading of the instruments on the bridge.

Because navigator makes the decisions, when it may not be possible to determine the probability distribution of future situations, he can use criterions: max - max, max-min or other.

The max-min criterion is assumed that there is possible the worst case (collision – pessimistic decision-maker). Thus, it is needed to choose the scenario for minimizing the effects of the collision.

3. Experimental approach to decision time

To estimate the time interval for taking and doing the decision, the research on full bridge simulator are done. This interval is considered in formula (4) to calculate the operator non-response probability.

Estimation of time interval has been done under assumptions:

- open water area,
- speed of own ship, v1=16 [knots],
- speed of target ship, v2=16.6 [knots],
- angle of courses' intersection = 90 [degrees],
- good visibility,
- no wind,
- sea's state - 0 [Beaufort scale].

The study was conducted on a group of 30 navigators of varying experience of the sea.

It was considered two variants:

Variant I - the own ship took precedence,

Variant II - the own ship gave precedence.

Furthermore, two variables have been considered:

n_{ZB} – the distance to the beginning of decision-making interval;

n_{NB} – the distance to the end of decision-making interval.

During the research, these distances have been estimated in two considered variants:

Variant I: nZBnp, nNBnp;

Variant II: nZBbp, nNBbp.

It has been shown, using appropriate statistical methods [2], that these distances are different in each of the variants, *Figure 3*.

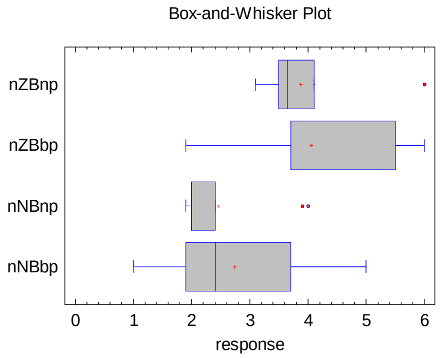

Figure 3. The Box-and-Whisker Plot

Box-and-whisker diagram (plot) is a convenient way of graphically depicting groups of numerical data through their five-number summaries: the smallest observation, lower quartile, median, upper quartile and largest observation, in descriptive statistics. It displays differences between populations without making any assumptions of the underlying statistical distribution (non-parametric). The five-number summary gives information about the location, spread and range of the observations. The diagram can be drawn either horizontally or vertically. The observations are from a univariate variables that were measured on an ordinal or interval scale.

Box and whisker plots are uniform in their use of the box: the bottom and top of the box are always the lower and upper quartiles, respectively, and the band near the middle of the box is always the median. But the ends of the whiskers can represent several possible alternative values, such as:

- the minimum and maximum of all the data,
- the lowest datum still within 1.5 IQR of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile,
- one standard deviation above and below the mean of the data,
- the 9th percentile and the 91st percentile,
- the 2nd percentile and the 98th percentile.

Any data which are not included between the whiskers should be plotted as an outlier with a dot, small circle, or star. Sometime the diagram includes an additional dot or a cross plotted inside of the box to represent the mean of the data in addition to the median. The box plot is a quick way of examining one or more sets of data graphically. It can be useful for handling many data values and allow to explore data and to draw informal conclusions when two or more variables are present. It shows only certain statistics rather than all the data.

For the analysis of variables n_{ZB} and n_{NB}, drawing *Figure 3*, median was adopted as a central point. You can see a significant difference in the length of the "whiskers" and the unbalanced position of the median for all variables showing a large right-sided asymmetry. Asymmetry of this precludes the normal distribution as a model because the distribution is perfectly symmetrical. Therefore, the modeling needs to use other distributions, such as:

- Birnbaum-Sauders distribution,
- Largest Extreme Value distribution,
- Inverse Gauss distribution,
- Weibull distribution.

In addition, you may notice a considerable variation in the torque (moment) the decision (both as to its adoption and implementation) in the case where the own ship should give priority to. Survey research has confirmed that this is the result of differences of time gaining experience in swimming on large units. Moreover, in the "priority", you can clearly see the presence of groups of subjects who present attitude of "underwriter”. A small scatter of results for the case "priority" can be interpreted as an expression of confidence in the foreign vessel for compliance with the Rules MPDM.

Table 2. The values of the variables t_{ZB}, t_{NB}

Variant I	t_{ZB}	0.2218 [h]
	t_{NB}	0.1313 [h]
Variant II	t_{ZB}	0.2406 [h]
	t_{NB}	0.1375 [h]

These values determine the time interval to make a decision and can be use in (4) – (5).

4. Optimizing the risk in the collision situation

When the time interval for making and doing the decision is given, it is possible to do the optimization of the collision risk for considered navigational situation.

To formulate the optimization task we assume that time for acceptance of danger for own ship is discreet random variable with known or easy to find distribution function.

According to the optimizing methods of operations research, for minimizing the risk of danger we assume:

$x_{i,j}^{r}$ - the decision variables, described in section 2,

t_{j}^{r} - the general time for decision, in r-th type of dangers, when the j-th target ship is considered.

Then the following limitations are needed:

$$\underset{i\in I}{\forall}\ \underset{r\in R}{\forall}\ \sum_{j\in J} x_{i,j}^{r} \le b_{j}^{r}, \tag{7}$$

$$\underset{j\in J}{\forall}\ \underset{r\in R}{\forall}\ t_{j}^{r} = \min\left\{\sum_{i\in I} x_{i,j}^{r} - \Psi(j), 0\right\} \tag{8}$$

$$\underset{j\in J}{\forall}\ \underset{r\in R}{\forall}\ \max\left\{\lambda_{i,j}^{r}\right\} < g_{j}^{r}, \tag{9}$$

$$\underset{i\in I}{\forall}\ \underset{j\in J}{\forall}\ \underset{r\in R}{\forall}\ x_{i,j}^{r} \ge 0, t_{j}^{r} \ge 0, \tag{10}$$

what gives the minimal risk of collision of *i-th* own ship with *j-th* target ship, in *r-th* type of collision as the objective function:

$$F = \sum_{i\in I}\sum_{j\in J}\sum_{r\in R}\left[\left(g_{j}^{r} - \lambda_{j}^{r}\right)\mu_{j}^{r} x_{i,j}^{r}\right]$$

$$- \sum_{j\in J}\sum_{r\in R}\left[g_{j}^{r}\left(\sum_{l\in U_{j}^{r}} p_{j}^{l,r}\mu_{j}^{r} t_{j}^{r}\right)\right]. \tag{11}$$

Formulated optimization task satisfies the conditions of the problem of integer mathematical programming.

The multi-criteria optimization methods can be divided into classical ones and ranking ones. The classical methods consist in integration of many criteria into one. Among other, the weighed criteria method belongs to the classical multi-criteria optimization methods. The weighed criteria method consists in reducing the multi-criteria optimization to one-criteria by introducing a substitute criterion in the form of the weighed sum of criteria.

5. Conclusion

The human errors are the one of the most important factors influenced the decision-making process on the sea. There is possible to use the methods and models for calculating the operator's reliability in navigational situation. In the paper, two models for finding the probability of operator's response are proposed. First, Rash model, is useful in the case, when navigator has the full information about the target ship. In this model time of perform the manoeuvre is not important. In the second model, HCR, the probability of operator's non-response is function of time. Thus, it is good approach to the estimate the values of operator's reliability in decision-making process based on the simulation.The results of simulation are presented and discussed. After all they have been used to minimize the risk of collision two ships.

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