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DECISION-MAKING IN VESSELS ROUTING

Passing particular route by the specific vessel is associated with a set of various types of parameters referring to data assigned to sectors situated along given route. Whenever alternative routes exist one has to upgrade hierarchy among available options and select the best one. Selection is a multi-criteria problem with deterministic as well as random values involved.

PODEJMOWANIE DECYZJI W PROCESIE WYBORU TRASY STATKU

Przejście statku wzdłuż pewnej trasy można opisać za pomocą zbioru różnego typu parametrów mających związek z danymi charakterystycznymi dla położonych wzdłuż danego przejścia stref kontroli. W przypadku istnienia alternatywnych tras powstaje problem ich oceny i wyboru najlepszego wariantu. Taki problem jest z natury wielokryterialny a typy poszczególnych parametrów obejmują przypadki deterministyczne jak i probabilistyczne.

1. INTRODUCTION

Operation area of sea going vessels can be divided into three major parts: port, restricted area and open sea. It appears that collisions and groundings create most serious problems for the environment. Record of well-known accidents with huge tankers involved proves the statement. Restricted area with heavy traffic is of special care for everyone involved in safe navigation. The case is worth exploring, and gained main focus in many reports and papers.

Based on collision risk model one can say that the probability of collision depends on crossing area topology as well as on an encounter rate. Encounter mean situation of penetrating domain area of any ship by another vessel. Any way of distributing the traffic that result in avoidance of local cumulating of ships should be considered beneficial for restricted areas since it leads to decreased number of encounters.

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Important is any reduction of encounter number for each vessel while passing restricted area. More important seems reduction of encounters involving huge vessels. The concept, which enables problems definition, may be based on zones of a special care. Such zones or sectors are those areas where it is considered necessary to maintain congestion free. The amount of traffic within a sector, at any time, should be kept below a predefined capacity value. Sectors are also likely to have some statistics assigned. Since they are areas of special care data referring to records of accidents happened within each of them along with local random traffic parameters are recorded and stored for further use. Local traffic data is very likely to be available.

The paper also exploits an idea of safety factors, which are assigned to each ship. The factor vary on an integer scale such that the higher the number the more disastrous the consequences of an accident.

Passing particular route by the specific vessel is associated with a set of various types of parameters. Whenever alternative routes exist one has to upgrade hierarchy among available options and select the best one. Undoubtedly the selection problem is multi-criteria one with deterministic as well as random values involved.

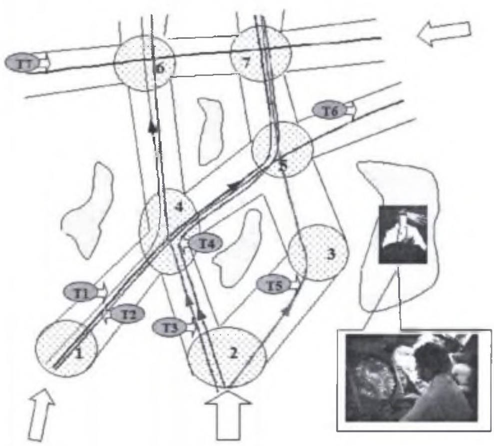

Fig.1. Sectors convert separation scheme into a network with a flow restriction

An example of restricted area with traffic separation is shown at figure 1. There are two main directions of flow with alternative routes for north and northeast bound vessels. The routes are labelled with T1, T2, T3 and so on. Masters have to decide on itinerary. Each one has to select a route to be taken considering a set of different and quite often conflicting criteria. Time of passage along with traffic encountered will be among the most important. Economic along with safety aspects are to be taken into account. Someone in charge of traffic managing at the local VTS control station will presumably be interested in overall assignment of the incoming vessels that reduce total number of close quarter situations. Congestion and delays free traffic allocations will be appreciated. In other words there are two main questions to be answered: what is the best route for particular vessel? what is best assignment of routes for particular set of vessels?

First question can be answered based on solution of decision-making problem under multiple objectives. The second is a bit more complicated and is itself multi-criteria optimisation problem. It was proved that, in single objective version, it belongs to the NP-complete class of the generalized allocation problems (GAP). Its solution produces Pareto optimal sets of decision variables. The sets must be subject to further analyses and at the final stage decisions are made.

2. MULTI-CRITERIA DECISIONS PROCESS

Multicriteria methods can be classified based on computational methodology. One can mention:

1. single-criterion methods, based on multi-attribute utility approach,
2. outranking methods which accept incomparability,
3. iterative, exploiting trial and error approach.

In the first approach each attribute has a weighting factor assigned. This aggregates all of the attributes into unique value or utility. Main disadvantage of the method is possibility of compensation, where large increase of least important attribute outweighs the most important one. The method is basic for TOPSIS (Technique for Order Performance by Similarity to Ideal Solution). As presented in [6] the approach was successfully utilized for sea routes selection problem.

First two methods are very popular, they require preferences to be known a priori, or there must be clear rules to deduce them as for example, in stochastic dominance. In this paper multi-criteria decision making in sea traffic engineering and directed at routes selections will be built using second method. ELECTRE software package, which exploits outranking method will be used for upgrading final hierarchy.

Multi-criteria decision-making involves four stages (see figure 2). Usually one has to consider:

- initial data sets preparation, this step is sometimes called as structuring of the decision making problem. In the discussed area this stage embraces collecting data from passage schedules and/or execution optimisation procedures,
- the preferences definition and modelling, as well as the determination of inter-criteria information. In TOPSIS creating expert matrix is important,
- upgrading hierarchy model. In TOPSIS Euclidian distances from ideal best and worst are calculated,
- generating the final decision.

There must be a feedback within decision-making process to enable primary factors to be identified and extracted.

The scheme is very much like in general approach to decision making. First phase leads to the identification of a finite set of alternatives and to the formulation of different sets of attributes to particular group of alternatives. The performances of the alternatives with regards to these attributes are contained in a performance table. The data contained in performance table are the main items to be processed. The elements of such table could be of any type mention: ordinary quantities, discrete/continuous random variables given as density probability functions as well as fuzzy numbers with membership functions.

The structuring phase ends up with formulation of the elements that will be used for the decision-maker's preferences modelling. The preferences modelling phase aims to build relational systems on the set of the alternatives that represent the preferences of the decision-maker. Modelling elements could be used to reflect the relative importance coefficients, indifference, preference and veto thresholds, etc. Multicriteria decision aids such as ELECTRE or PROMETHEE methods can be used at this stage. Both of them enable upgrading valued outranking relation.

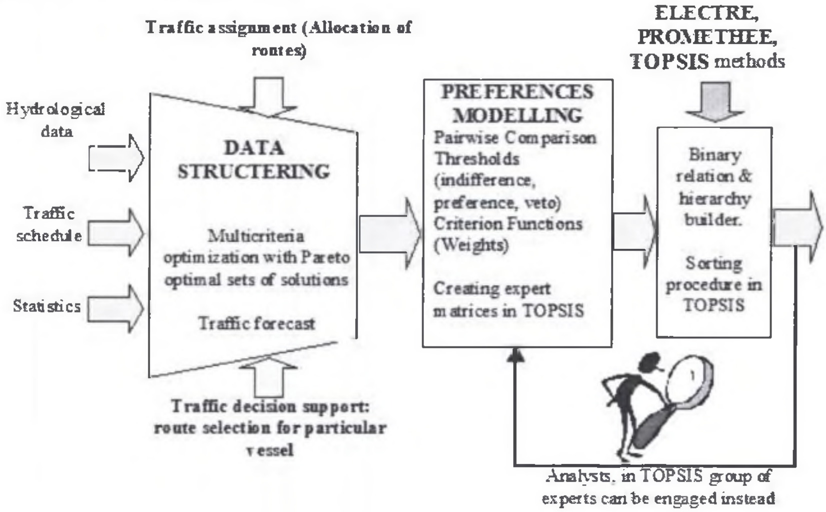

Fig.2. Multi-criteria decision making in sea traffic engineering involves four stages

3. ROUTES SELECTION

Ship's route is a sequence of legs joining turning and/or crossing areas that can be treated as zones of special care or sectors. The idea was proposed by Goodwin and Richardson [1], and proved to be important whenever formal approach toward traffic assignment is discussed.

For particular vessel and each route, she is assumed to take, time of passage and scheduled traffic are presumably known. Apart from these deterministic parameters there are forecasts regarding local traffic along with accidents statistics for selected regions. To take proper choice, assumed a few options exist one has to compare a handful of parameters of different nature. There are deterministic values, forecast empirical sets and probability functions to be dealt with.

There are quite many methods available that can be used to make order among available alternatives. The simplest way of approach is to combine objectives into a single function. Usually each objective receives its weight and the function is a polynomial, which minimal (maximal) value is sought. Multiple attribute utility theory (MAUT) is the basic one that enables creating function to order actions from best to worst. The method proved to be popular since incomparability of criteria does not eliminate its usage. One has to consider time of passage, number of encounters observed and another included in the set of possible attributes. Incomparability was the main reason that made researches to modify direct approach typical for MAUT.

Outranking methods inherently able to cope with incomparability had been developed. They are also free of the compensation problem. An outranking binary relation defined for two arguments (actions) stipulates as follow [2]: "Given what is known about the decision maker's preferences and given the quality of the valuations of the actions and the nature of the problem, there are enough arguments to decide that first is at least as good as the second, while there is no essential reason to refute that statement". In ELECTRE indifference, preference and veto thresholds are to be defined. The veto value, if exceeded, enables denying preference regardless to any other relations.

3.1. STOCHASTIC DOMINANCE

Stochastic dominance can be developed based on population probability distribution. Probabilistic data comparison engages first and second degree dominance. For descending direction of preferences first degree stochastic dominance is defined as [3]: "Given two probability distributions A and B, A dominates B when for all x cumulative probability under A distribution is smaller than or equal to cumulative probability under B distribution. There are some x where strict inequality is found".

Second degree stochastic dominance is defined as: "Given two probability distributions A and B, A dominates B when for all x cumulated cumulative (integral of cumulative probability) probability under A distribution is smaller than or equal to cumulated cumulative probability under B distribution. As before, there must be some x where strict inequality is found".

Let us concentrate on comparison of two routes, which are considered while passing particular area. Each of them consists of ten nodes numbers of another crafts met at each leg are available based upon forecast traffic. There are example sets of data presented in the following table. Columns titles meaning is as follows:

- Route A (B) - One of the alternative route,
- Encount. - Consecutive numbers of ships encountered within sectors,
- Freq. A (B) - Frequency of encounters for A (B) route,
- Prob. A (B) - Probability of given number of encounters for A(B) route,
- Cprob. A (B) - Cumulative probability of given encounter numbers for A(B) route,
- Ccprob. A (B)- Cumulated cumulative probability of given number of encounters for A(B) route.

Table 1

Example of two sets of close quarter encounters for alternative routes.
Second degree stochastic dominance is observed for route B from shaded cells

No	route A	route B	Encount	Freq. A	Freq. B	Prob. A	Prob. B	Cprob. A	Cprob. B	Ccprob. A	Ccprob. B
1	0	0	0	1	2	0,1	0,2	0,1	0,2	0,1	0,2
2	1	2	1	1	0	0,1	0	0,2	0,2	0,3	0.4
3	2	0	2	2	1	0,2	0,1	0.4	0.3	0.7	0.7
4	2	3	3	0	1	0	0,1	0,4	0,4	1,1	1.1
5	4	8	4	1	3	0,1	0,3	0,5	0,7	1,6	1.8
6	5	4	5	1	0	0,1	0	0,6	0,7	2,2	2.5
7	6	4	6	2	1	0,2	0,1	0,8	0,8	3	3.3
8	6	4	7	2	1	0,2	0,1	1	0.9	4	4.2
9	7	6	8	0	1	0	0,1	1	1	5	5.2
10	7	7	9	0	0	0	0	1	1	6	6.2
Total	40	38	T. F.	10	10						
			T. E.	40	38						

These sets represent data for two alternative routes, which are supposed to be taken by a vessel. Each route consists of ten nodes. Figures included in the left parts of the presented table are forecast numbers of close quarter encounters occurred within each node. Applying common sense rule one can state that "the lower total number the better alternative". Stochastic dominance theory quite often contradicts such statement.

Let us consider number of encounters presented in the left hand, shaded part of the table 1. Second column *route A* shows expected encounters for route A, third one *route B* contains respective data for route B. Should one select route B as better since total encounters number (38) is smaller than that for route A (40). First-degree stochastic dominance does not confirm the judgement. Since cumulative probability for the second option (column *Cprob. B* in table 1) for some points does not exceed this for the first one for each point one should not make the final decision. The second-degree stochastic dominance confirms that taking route B if preferred to selecting the first case. Column *Ccprob. B* at table 1 contains greater than or equal figures compare to those in column *Ccprob. A*, so second degree stochastic dominance is observed.

Same as for deterministic values there are three ranges of values suggested for non-deterministic comparison. Contrary to the deterministic case strict threshold values do not exist. Proposed scheme is based on stochastic dominance, ranges of values overlap their neighbours. Exception is boundary between veto and strong dominance regions. Ambiguity is resolved based on cumulative distribution. Area of indifference is defined based on disability of establishing stochastic dominance. Neither first nor second degree stochastic produces decisive output. Weak dominance requires second-degree stochastic dominance to be observed. Strong dominance of one action over another one requires that the final relation could be concluded based on the first-degree stochastic dominance. Veto will take place under the same condition as strong dominance. The last two cases differ with regard to mean values. Threshold value plus first-degree dominance decide about veto of one action over another one.

Although stochastic indifference, weak and strong dominance were established based on first and second degree dominance real cases sometimes contradict this straightforward assumption. One can be disappointed when considering case of two routes. Let us assume that at the first one vessel meets three crafts at each node (total 30 encounters). Taking another passage zero encounters is noticed once and at each of all remaining node ten vessels are expected (90 encounters). Surprisingly proposed approach does not confirm supremacy of the first case. Due to greater values for initial points for cumulative as well as for integrated cumulative probabilities one can conclude that the two cases are indifferent! Comparing mean values proves something extremely opposite. These illustrate that main guideline when upgrading hierarchy among stochastic parameters are mean values. Both degrees of stochastic dominance are to be treated as secondary factor.

Contrary to experimental data theoretical density functions do not cause any ambiguity. Same as for experimental data comparison of two normally distributed random values might be based on cumulative and integrated cumulative probability.

Let us consider options of five routes to be decided on one of them as shown in table 2. There are four weighted criteria with coefficients presented in the title row of the table along with the criterion name. Presented in consecutive columns data mean:

1. route number (Route),
2. passage time (PT),
3. number of encounters of ships with safety factor greater than 5 (ESF5),
4. number of encounters of ships with safety factor greater than 5, which will occur in the area of special concern (ESF5X),
5. number of encounters with local traffic (LE) forecast for consecutive node. This is non-deterministic set of parameters given as forecast number of encounters for each of six nodes of the route within separation scheme.

There are decision maker preferences regarding each criterion. Indifference, preference and veto thresholds are specified for each of them. For criterion of encounters of ships with safety factor greater than 5 (ESF5) values of weight, indifference, preference and veto thresholds respectively are 0.3/2/4/7. None of the assignment can be considered supreme to another if its ESF5 factor is greater for more than 7. The highest concern (ratio 0.35) is attributed to encounters of vessels with larger than 5 safety factors, which are scheduled to take place within particular area called X. The lowest factor was assigned to LE criterion. In this case indifference and dominance thresholds were not specified since relations rely on outcome of the second and the first-degree dominance calculations. Nonetheless veto threshold is included.

Table 2

Example of routes allocation set

Route	PT /0.25/15/30/-	ESF5 /0.3/2/4/7	ESF5X /0.35/1/2/-	LE /0.2/-/-/12
T01	290	19	7	(2,3,0,2,4,5) 16
T02	295	21	6	(4,5,2,3,0,6) 20
T03	325	15	9	(2,4,2,5,6,3) 22
T04	300	13	10	(3,2,3,2,3,1) 14
T05	270	15	9	(2,1,3,0,2,3) 11

Final result generated by software implementing principles of ELECTRE method is shown at figure 3. Presented ranking shows route T05 as the supreme one at the highest level. This route should be recommended as the best one. Nodes at the same level are of the equal rank. One cannot tell the preference of T04 over T01 or T04 over T02, nor can treat them as indifferent. Positions of T04 and T02 within the graph are determined by veto threshold with respect to ESF5 criterion. Dominance of T02 over T04 is refused due to extreme increase of encounters with big ships.

Second level of the hierarchy consists of incomparable alternatives with respect to the considered set of comparisons of routes T01 (T02) and T04. All of them are dominated by alternative T05. Nevertheless relation between T01 and T02 is clear. The worst, placed at the lowest level, is route T03.

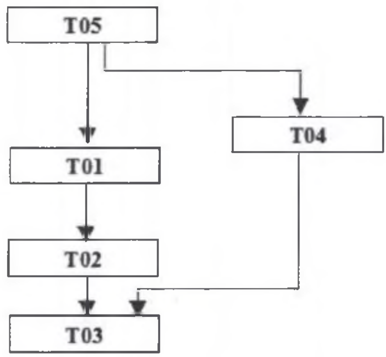

Fig.3. Graph of solution generated by the available software using ELECTRE III method

4. ROUTES ASSIGNMENT

The concept of routes assignment is based on zones of a special care or sectors. It is assumed that amount of traffic within a sector should be kept below predefined level referred as capacity. This constraint in routes assignment is substantial and creates opportunity for formulation optimisation problems. These are very much different from previously discussed selection of route. Introducing the concept of sectors within scheme of routes converts it into a network with the flow restriction.

Passing particular route by the specific vessel can be associated with cost value. Primary cost function may be related to the time passage of ship with the safety factor along route. Passage along prescribed routes by each of vessels will be associated with another factor that can reflect number of encounters occurred during the execution of the recommended assignment. Among different categories of close quarter approaches those with large ships involved are most important and should be avoided. Routes assignment appears as optimisation problem in which minimization of criteria related to encounters along with total passage time are sought. Constraints of keeping sectors' load below its capacity must be observed. Approach proposed by the author is to adjust distribution through selection of routes to be passed while maintaining speed unchanged. Assignment of route to each of the vessels for which capacity of sectors are not violated at any moment and the cost functions are minimal is searched. More details can be found in the author's paper [4][5].

5. FINAL REMARKS

Reduction of close quarter approaches number may result from introducing separation schemes with alternative routes. Selecting best one to follow is a multi-criteria choice. The process consists of a few steps, mention: data structuring, thresholds values assignment and upgrading final hierarchy. Data structuring for the case of route selection is rather simple and invokes procedures that prepare schedule of forecast traffic. The schedule can include some statistical and/or experimental data. The next step is to decide on indifference, preference and veto thresholds. One has to engage stochastic dominance theory to create the final hierarchy. Comparison of cumulative and integrated cumulative densities may bring about some ambiguity when experimental data are processed. Theoretical probability functions are rather free of this drawback. Outranking ELECTRE methods may be used to generate result graph of hierarchy.

Multi-criteria decision-making is also final stage when dealing with traffic assignment for a given set of vessels. The phase of structuring the input data is different than in the route selection. Problem is much more complex and reference to theory and practice of multi-criteria optimisation is inevitable. The output of the multi-criteria optimisation consists of rather numerous set of Pareto optimal solutions. The set is a subject to further processing and is assumed to deliver data for structuring phase of the decision making process.

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