ISSN 0209-2069

ZESZYTY NAUKOWE NR 2 (74)
AKADEMII MORSKIEJ
W SZCZECINIE

EXPLO-SHIP 2004

Włodzimierz Filipowicz

Multicriteria Optimization and Evolutionary Algorithms in Traffic Engineering

Key words: optimization, multicriteria decision making, traffic control

Separation schemes along with Vessel Traffic Services have improved the safety of navigation, particularly within restricted waters. Their role is rather passive and common sense is still required whenever a decision is to be made. It is assumed that it could be beneficial in terms of collision or accident risk reduction once active measures are introduced. The concept raises a wide variety of problems that are to be discussed, defined and solved.

Optymalizacja wielokryterialna i algorytmy ewolucyjne w inżynierii ruchu statków

Słowa kluczowe: optymalizacja, podejmowanie decyzji w warunkach wielokryterialnych, kontrola ruchu

Systemy separacji wraz ze służbami ruchu przyczyniły się w znaczący sposób do poprawy bezpieczeństwa ruchu statków w rejonach ograniczonych. W większości przypadków ich rola jest pasywna a zdrowy rozsądek dominuje jako główny element podczas podejmowania jakichkolwiek decyzji. Zakłada się, że wprowadzenie systemu o charakterze aktywnym opartym na solidnych podstawach teoretycznych z zakresu podejmowania decyzji przyczyni się do redukcji ryzyka kolizji czy wypadku morskiego. Takie podejście rodzi jednak szereg problemów, które powinny być zdefiniowane, rozwiązane a następnie implementowane.

Introduction

Studies discussed in many papers, e.g. [9], report that human involvement in all marine accidents remain very high. One of the reports said that human error was the main cause of 90% of all collisions. A closer look at the nature of errors indicates information processing along with high situational stress as accounting for 84% of accidents. Having identified the main reason, one can try to introduce measures to improve the situation. A wider use of computers and computer networks should reduce data processing faults. Additionally, automatic control should decrease the level of stress. These ideas are to be implemented within Vessels Traffic Systems, whose role is essential in improving safety standards.

The 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 the biggest problem for the environment. Records of well-known accidents of huge tankers proves the statement. The restricted area with heavy traffic calls forspecial caution to be exercised by everyone involved in safe navigation. The case is worth exploring, and was the focus in many reports and papers.

Anderson and Lin [1] developed a collision risk model; the survey was done for three dimensions air traffic. Their formula that reflects the probability of collision at intersection area says that the probability of collision depends on crossing area topology as well as on the encounter rate. An encounter means a situation of penetrating the domain area of any ship by another vessel. Any way of distributing the traffic that results in avoidance of local concentration of ships should be considered vital for restricted areas since it leads to a decreased number of encounters.

It is important to reduce the number of encounters n for each vessel while passing a restricted area. More important, however, seems to be the reduction of encounters involving huge vessels. The concept, which enables the problem definition, may be based on zones of 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. Passing a particular route by the specific vessel is associated with a set of parameters. Usually the higher a figure the less recommended is the passage.

1. The Concept

The fundamental concept is based on zones of special care, first proposed by Goodwin [7]. The concept was exploited by the author and presented in [5, 6]. Such limited areas, called sectors, are those where it is considered necessary to control the movement of ships. Amount of traffic within a sector should be kept below its capacity. The amount can be a basic measure wherever the quality of traffic assignment is considered. Every ship coming within the area has a safety factor number assigned to it. The factor will vary on an integer scale such that the higher the number, the more disastrous the consequences of an accident. Arbitrarily assigned safety factors were presented in previous papers. The sum of the safety factor numbers of ships inside the zone is called the load of the sector. An excessive load of sectors is to be avoided whenever possible. Sectors are also likely to have some statistics assigned. Since they are areas of special care, data referring to accidents that happened within each of them along with local random traffic parameters are to be collected and stored for further use. Apart from this, each sector has quasi-deterministic attributes calculated on the basis of forecast traffic. Such attributes will be related to encounters categories and safety factors of ships involved.

Introducing the concept of sectors, the system of routes in the area can be treated as a network with restrictions on the flow. Such an approach raises a wide variety of problems, which are to be formulated and finally solved and some of them implemented.

The new separation scheme is to embrace new elements such as sectors and possibly alternative routes. From the point of view of a single vessel, one will have to decide which route to take. Looking at the area from the traffic manager point of view, it will be important to avoid local congestions and allocate the incoming flow accordingly. To achieve this one may adopt some of the published solutions devoted to stochastic networks. The Stochastic Multiobjective Shortest Path algorithm developed in [8, 11] is a good candidate for alternative routes environment where best passage conditions for particular vessel is sought.

2. Problems and Assumptions

Passing a particular route by a specific vessel can be associated with the so called cost value. The higher the cost, the less recommended is the passage. For instance, a fully loaded tanker steaming through a narrow channel, although possible, will be considered “costly”. Higher cost value will be also assigned to a vessel that for some reason remains longer in the area than necessary. Steaming along a shorter route is generally preferred over the longer one. The cost function should also reflect local preferences and is considered to depend on the type, length and cargo of the vessel as well as depth and breadth of the channels. A passage along a given route by a particular vessel can be associated with cost value that reflects the number of encounters that occurred during the passage. Among different categories of close quarter approaches, those with large ships involved are most important. Finally, passages can be characterized by a set of non-deterministic parameters.

For the reasons stated before, control or decision making problems regarding vessels traffic must be considered as multicriteria ones.

The given criteria are: system of routes with statistics of local traffic at its nodes, maximum allowed capacity along with random parameters (if any) for each sector, set of vessels with a safety factor numbers assigned, a timetable of passage. Due to a variation of speed and unforeseen deviation from the prescribed track, arrival as well as departure times at each sector changes around an estimated value.

2.1. Questions of Decision Making and Control Problems

There are two main questions, which traffic manager should answer:

1. What is the best route for a particular vessel?
2. What are the best routes allocated to a particular set of vessels?

The former question can be answered on the basisof the solution of decision making problem under multiple objectives. The latter is an optimization problem, which belongs to the NP-complete class of the generalized allocation problems (GAP). The problem was discussed in previous author's paper [6]. Multicriteria approach stipulates that its first step of solution produces Pareto optimal sets of decision variables, the next and final stage engages decision making.

3. Multiobjective Approach

Most real problems are multiobjective ones, those with many criteria. To satisfy each of them at the same time is usually simply impossible since they are conflicting quite often. In the discussed problem, besides minimizing overall cost function, the decision maker can be interested in a situation within a particular area or in a passage of particular vessel. The objective should additionally penalize encounters of vessels with high safety factors. Extra penalty might be applied if too many vessels are gathered in an area of special concern. In other words, each allocation of routes is subject to a variety of assessments. Here are the criteria that are to be considered for the sake of selecting the best route:

- passage time,
- number of encounters regarding particular classes of vessels,
- number of ships present in the area of special concern from local authorities' point of view, which means a particular set of sectors and surrounding waters,
- maximum load of sector,
- amount of random local traffic encountered.

4. Evolutionary Algorithms

Metaheuristcs or extended heuristics became very important optimization tools. These algorithms require powerful computers to obtain solution close to an optimal value within reasonable time. On the other hand, they are able to produce satisfactory output run on available PCs. One of the approaches called Population Learning Algorithms (PLA for short) is based on an idea that lies behind social education systems. The computation scheme enables combining different optimization techniques. As in a normal education system, PLAs start with basic level training applied to randomly selected individuals. Promoted are those which pass necessary tests and satisfy promotion criteria. Subsequent stages of education involve more sophisticated methods of education as well as more difficult criteria of selection. The number of educated individuals can vary from stage to stage. Contrary to their natural counterpart this number can increase. The best from the final stage population is a solution. The whole process of individual's improvement is carried out according to specific scenario of education or solving a problem. Scenarios play an important role in PLA computations. Carefully selected and implemented, they can bring expected results within reasonable time. The case of choosing "first to fit" scenario can result in unacceptable outcome. In this respect scenarios are to be treated as problem oriented.

PLAs work with individuals very much like other genetic algorithms. Proper representation of an individual is important and it should be liable to crossover, mutation and other problem specific operators. Evolutionary algorithms are particularly suitable to solve multiobjective problems since they deal with individuals within a population. This allows to verify each of them regarding a wide scope of criteria. This is associated with good quality of the produced results that make these algorithms popular.

Individuals that improve any of the goal functions compose the so called Pareto optimal or non-dominated set of solutions. One allocation dominates another if it is better for one criterion and not worse for any other. The idea has a simple graphic representation. Let us consider a relationship (shown in Figure 1) between the probability of malfunctions of produced elements and the amount of money spent on research. Both are very much conflicting and are supposed to be minimized. At point (1) the money invested is almost minimal but at the same point the probability of malfunction is rather high. The opposite conditions are at point (2), the probability of failure is small but the cost is high. Points (1) and (2) are situated on the dashed line which is called Pareto-optimal front. None of the solutions at the front can dominate each another. Points outside the front, for example (3) and (4), are dominated by those at the dashed border.

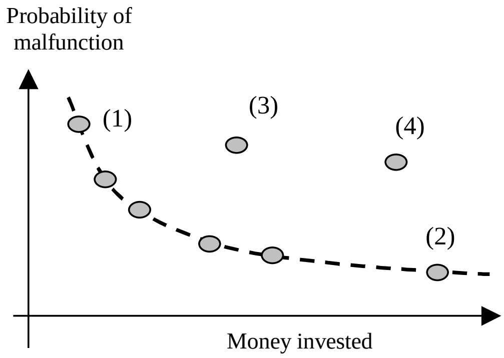

Fig. 1. Relationship between probability of malfunctions of produced elements and amount of money spent on research is an example of conflicting goals
Rys. 1. Zależność pomiędzy prawdopodobieństwem uszkodzenia a nakładami na badania to typowy przykład sprzecznych celów

Contrary to single criteria optimization problems, the solutions of multi-objective ones consist of sets containing much more than one vector of decision variables.

5. Decision making

For the reasons stated before multiobjective approach toward optimization usually involves at least two stages: search for non-dominated vectors and decision-making. The stages are usually considered separately. At the final step, the decision maker has to select one of the available options, presumably the best, present in the Pareto optimal set. There are quite many methods available that can be readily used. 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, whose minimal (maximal) value is sought. The method can be adopted wherever comparable criteria are taken into account. Incomparability eliminates the use of the method. One cannot compare directly the total cost function (in units of time) with the load of sector (relative measure given as a consumed percentage of total capacity). Incomparability made the author direct toward other approaches. Outranking methods have been developed to cope with such cases.

An outranking binary relation defined for two arguments (actions) stipulates as follow [10]: "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".

There are series of ELECTRE methods, which were upgraded for multicriteria selection. The aim of these methods is to create a subset (as small as possible) of actions, whose elements outrank at least one action being outside this subset. Fundamental for the methods are concordance and discordance matrices. For each pair of actions there is an assigned concordance index. The index can be understood as a measure of correctness of the statement "first is better then second" or "x outranks y". Since there are criteria which are doubtful from the point of view of the possibility of comparison the discordance index was introduced. This also enables proper approach towards the extremes. The discordance index increases if preference of one action becomes very large over the second one for at least one criterion from among comparable ones. A set contains pairs of extreme values for which preferences are refused regardless of the results of another comparison.

In ELECTRE III indifference, preference and veto thresholds appear (see Fig. 2) These shift the approach towards pseudo-criteria and outranking credibility. The idea contributes to the flexibility of the approach. The veto value, if exceeded, enables denying preference regardless of any other relations.

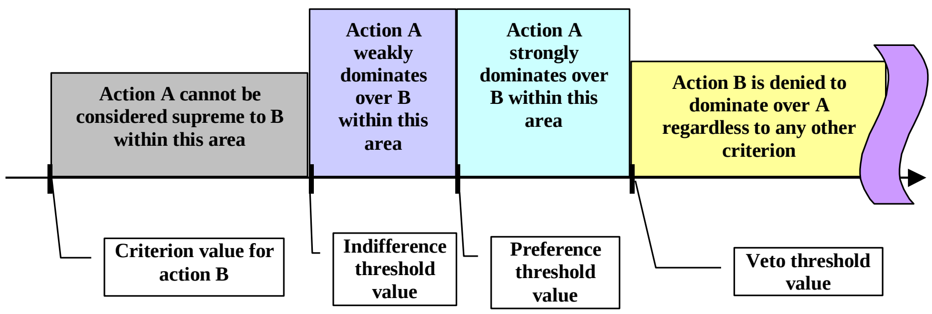

Fig. 2. There are three threshold values defined for deterministic comparison in ELECTRE III method

Rys. 2. W ELECTRE III zdefiniowano trzy wartości progowe dla porównania wielkości deterministycznych

5.1. Comparison of non-deterministic values

A comparison of two normally distributed random values (with mean μ and variance ν) might be based on cumulative probability. Analyses shown below are for the case in which $\mu_2 > \mu_1$, $\mu_2 - \mu_1 = 1$, $\nu_1 = 1$, $\nu_2 = 1$.

Figure 3 shows the density and distribution for ($\mu_2 - \mu_1 = 1$, $\nu_1 = 3(\mu_2 - \mu_1) = 3\nu_2$, $\nu_2 = 1$). First parameter is to be considered better than the second up to the probability of around 0.7. Appropriate probability values for wider range of differences of variances are shown in the top right corner of Figure 5. The rectangle in the corner refers to $\nu_1 = 1.5\,\nu_2$ with probability ~0.98. The arrow at this part of the figure indicates the direction of changes due to the increment of the difference of variances.

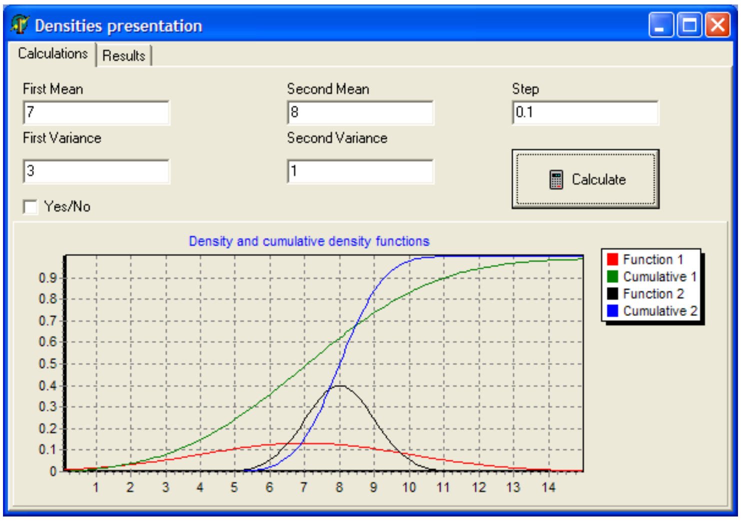

Fig. 3. The comparison of two normally distributed random values might be based on cumulative probability ($\mu_1 = 7$, $\mu_2 = 8$, $\nu_1 = 3(\mu_2 - \mu_1) = 3\,\nu_2$, $\nu_2 = 1$)

Rys. 3. Porównanie dwóch zmiennych losowych o rozkładach normalnych można przeprowadzić na podstawie ich dystrybuanty (pokazano przypadek $\mu_1 = 7$, $\mu_2 = 8$, $\nu_1 = 3(\mu_2 - \mu_1) = 3\,\nu_2$, $\nu_2 = 1$)

Figure 4 shows the density and distribution for ($\mu_1 = 7$, $\mu_2 = 8$, $\nu_1 = 1$, $\nu_2 = 3(\mu_2 - \mu_1) = 3\,\nu_1$). The second parameter is to be considered as better than the second up to the probability of around 0.3. Appropriate probability values for wider range of differences of variances are shown in the bottom left corner of Figure 5. The rectangle at the corner refers to $\nu_2 = 1.5\,\nu_1$ with probability ~0.02. The arrow at this part of the chart indicates the direction of changes due to the increment of the variance of the second parameter.

It is clear that a comparison of two normally distributed random values might be clear due to the comparison of means and relatively small variances difference. It proves to be ambiguous in the case of a large difference of variances. An appropriate range of probabilities is to be introduced for the definite judgement.

The same as for deterministic values, there are three threshold values suggested for non-deterministic comparison (see Figure 6). These threshold values refer to the mean ones. The area of indifference is defined on the basis of these values. A weak dominance requires comparison of variances along with range of probability in which it is to be observed. The dominance could be denied within the marked area due to a large difference of variances. A strong dominance requires the comparison of variances. The range of probability in which dominance is observed is supposed to be wide, say <0.01; 0.99>. The dominance could be denied within the marked area due to extreme variances. The veto is likely to take place in case of a large difference of mean values and small variances. The veto could be also denied due to extreme variances.

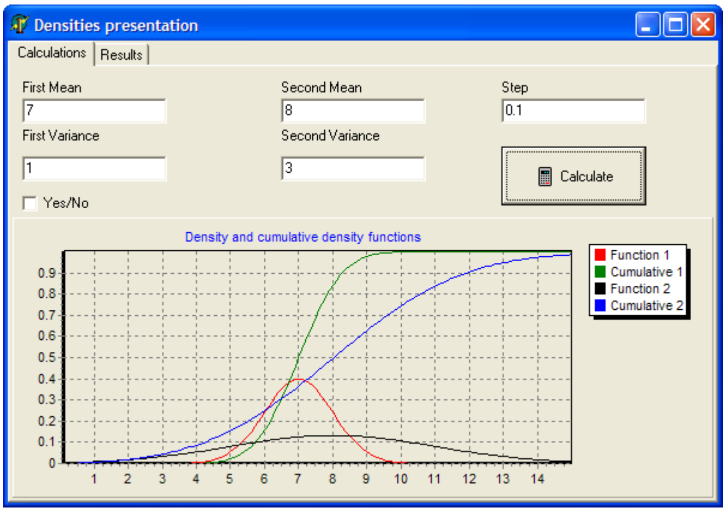

Fig. 4. Comparison of two normally distributed random values might be based on cumulative probability (for the example $\mu_1 = 7$, $\mu_2 = 8$, $\nu_1 = 1$, $\nu_2 = 3(\mu_2 - \mu_1) = 3\nu_1$)

Rys. 4. Porównanie dwóch zmiennych losowych o rozkładach normalnych można przeprowadzić na podstawie ich dystrybuanty (pokazano przypadek $\mu_1 = 7$, $\mu_2 = 8$, $\nu_1 = 1$, $\nu_2 = 3(\mu_2 - \mu_1 = 3\nu_1)$*)*

Let us consider routes allocation as a non-dominated set as shown in Table 1. There are five weighted criteria with coefficients presented in the title row of the table along with the criterion name. The data presented in the consecutive columns denote:

1) allocation number (Allocation),
2) calculated total passage time (PT),
3) number of encounters of ships with safety factor greater than 5 involved (ESF5),
4) number of encounters of ships with safety factor greater than 4 involved, which occurred in the area of special concern (ESF5X),
5) maximal, relative load of sector (ML) (ratio of *maximal load/capacity*),

6) number of encounters with local traffic (LE). This is non-deterministic parameter for which means and variances are given.

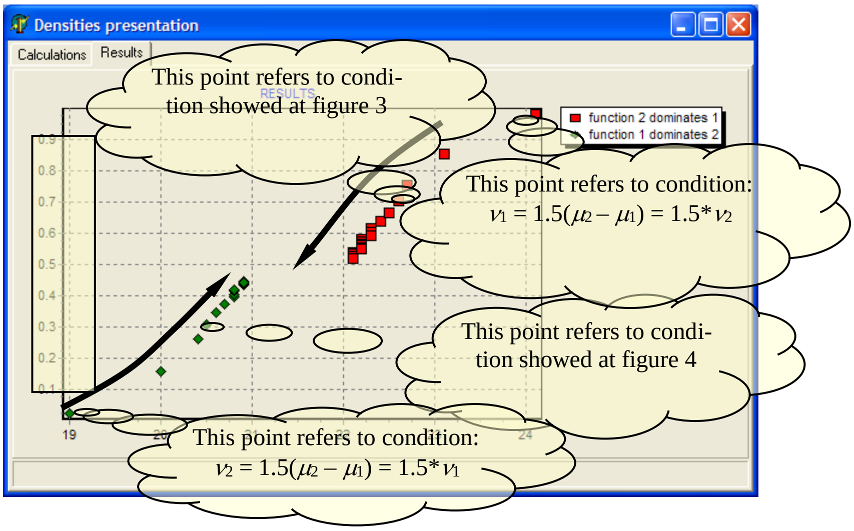

Fig. 5. Comparison of two normally distributed random values might be doubtful in the case of large variances difference

Rys. 5. Porównanie dwóch zmiennych losowych o rozkładach normalnych może budzić wątpliwości przy znacznych różnicach wariancji

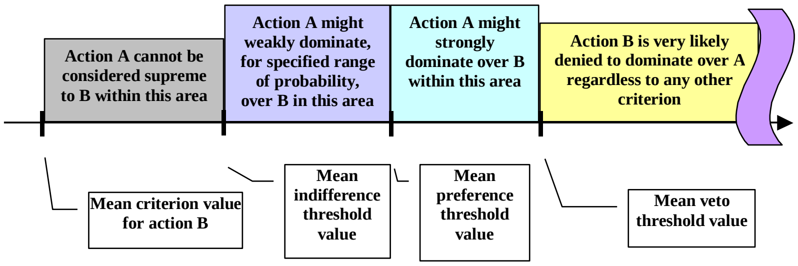

Fig. 6. There are three threshold values suggested for non-deterministic comparison

Rys. 6. Podobnie jak dla przypadku deterministycznego określa się trzy wartości progowe dla parametrów losowych

Indifference, preference and veto thresholds are also specified for each criterion. The highest concern (ratio 0.35) is attributed to encounters of vessels with larger safety factors within particular area called X. The set of Pareto optimal solution embraces five numbered records named from A0001 to A0005. There are decision maker preferences specified for each criterion. For the criterion of encounters of ships with safety factor greater than 5 involved (ESF5), the values of weight, indifference, preference and veto thresholds are, respectively, 0.3/2/4/7. None of the assignments can be considered supreme to another if its ESF5 factor is greater more than 7 (see veto point in Figure 6).

Table 7

Example of Routes Allocations Set
Przykład niezdominowanego zbioru rozwiązań problemu alokacji tras

Allocation	TP /0.25/10/20/-	ESF5 /0.3/2/4/7	ESF5X /0.35/1/2/-	ML /0.1/5/20/-	LE /0.2/10/20/-
A0001	290	19	7	75%	10/2
A0002	295	21	6	81%	15/2
A0003	325	15	9	80%	27/2
A0004	300	13	10	82%	19/2
A0005	270	15	9	70%	14/2

The result generated by software implementing principles of the ELECTRE III method is shown in Figure 7. The presented ranking shows allocations A0005 at the highest level. The nodes at the same level are of the equal rank. The allocations A0005 should be treated as the best ones. One cannot tell the preference of A0004 over A0001 or A0004 over A0002, nor can treat them as indifferent. The second level consists of equal allocations A0001 and A0004 with respect to the considered set of comparisons. Both are dominated by A0005. The worst, placed at the lowest level, is the allocation A0003. The relation between A0001 and A0002 is also clear.

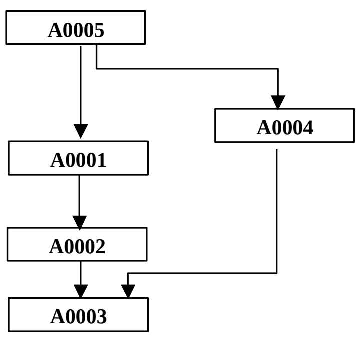

Fig. 7. The graph of solution generated by the available software using ELECTRE III method
Rys. 7. Diagram rozwiązania wygenerowanego przez dostępne oprogramowanie z użyciem metody ELECTRE III

Summary

Multicriteria decision making is the final stage when dealing with traffic assignment. One can consider single vessel and a dilemma which route to follow. The routes allocation problem is momre complex when one has to cope with a group of vessels. A large set of vessels and complicated structure of the separation scheme with NP-complete nature of the problem requires evolutionary approach to be considered and implemented.

The criteria taken into account are deterministic and probabilistic ones. To construct the final hierarchy among probabilistic values, one has to compare cumulative densities functions and to introduce the probability range.

The multiple attribute utility theory that enables creating a function to order allocations from best to worst could be adopted in the case of comparable criteria. Incomparability eliminates the use of the method. One cannot compare the total cost function (in units of time) with the load of sector (relative measure given as a consumed percentage of total capacity). Outranking methods have been developed to cope with incomparability. Therefore, they are considered suitable for the discussed problems. The ELECTRE methods appear to produce readily interpreted output even for robust sets of Pareto optimal solutions.

References

1. Anderson D., X. G. Lin, *A Collision Risk Model for a Crossing Track Separation Methodology*, Journal of Navigation, vol. 49/ 3, Londyn 1999.
2. Degre T., "The Management of Marine Traffic, A Survey of Current Future Measures", Journal of Navigation vol. 48, Londyn 1999.
3. Filipowicz W., *Traffic Control Problem – PLA Approach*, Proceedings of the 3rd International Congress on Maritime Technological Innovations and Research, Bilbao 2002.
4. Filipowicz W., *Vessels Traffic Control Within Restricted Areas*, Proceedings of the 3rd International Conference MMAR'2003, Międzyzdroje 2003.
5. Filipowicz W., *Minimizing Risk Probability For Vessels Traffic Control*, Proceedings of the 3rd International Conference TST' 03 Transport Systems Telematics, Katowice 2003.
6. Filipowicz W., *Vessels Traffic Control Problems*, Journal of Navigation, vol. 57/1, Londyn 2004.
7. Goodwin E., Richardson R.B., *Strategies for Marine Traffic*, Journal of Navigation, vol. 33, Londyn 1980.
8. Nozick L.K., List G.F., Turnquist M.A., *Integrated Routing and Scheduling in Hazardous Materials Transportation*, Transportation Science vol. 31/3, 1997.

9. Shea I.P., Grady N., *Shipboard Organisational Culture in the Merchant Marine Industry*, Proceedings of the Safe Navigation Beyond 2000, Gdynia 1998.
10. Vincke P., Gassner M., Roy B., *Multicriteria Decision Aid*, John Wiley & Sons, Nowy York, 1992.
11. Wijeratne A.B., Turnquist M.A., Mirchandani P.B., *Multiobjective Routing of Hazardous Materials in Stochastic Networks*, European Journal of Operational Research Vol. 65, 1993.

Wpłynęło do redakcji w lutym 2004 r.

Recenzenci

dr hab. inż. Roman Śmierzchalski, prof. AM
prof. dr hab. inż. Bernard Wiśniewski

Adres Autora

dr inż. kpt.ż.w. Włodzimierz Filipowicz, prof. AM
Wydział Nawigacyjny
Katedra Podstaw Informatyki i Sieci Komputerowych
Akademia Morska w Gdyni
ul. Morska 81/83
e-mail: wlofil@am.gdynia.pl