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Vessel Traffic Control Problems

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Separation schemes together with Vessel Traffic Services improve existing standards. Since their role has proved to be rather passive it is assumed that the introduction of active measures could be beneficial and improvement in terms of collision or accident risk reduction is expected. The concept raises a wide variety of problems that are to be discussed, defined and solved.

KEY WORDS

1. Separation schemes. 2. Safety factors. 3. Vessel traffic control.

1. INTRODUCTION. Many studies, for example [14], report that human involvement in marine accidents remains at a very high level and human error has been quoted as the main cause in 90% of all collisions. Each collision or other accident poses a serious threat to the environment. Closer look at the nature of errors indicates that information processing along with high situational stress accounts for 84% of accidents. Having identified the main reason one can try to introduce measures to improve the situation. Wider use of computers and computer networks should reduce data processing faults. Additionally automatic control should decrease stress levels. These ideas are to be implemented within vessel traffic systems, which have a basic role in improving safety standards.

The operational areas 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 problems for the environment. The record of well-documented accidents with huge tankers proves the statement. A list of potential risks to the environment is in Table 1 which also includes an arbitrary assessment of risk level. Heavy traffic in restricted areas requires special care for everyone involved in safe navigation. The case is worth exploring and for this reason it is the main focus in this paper.

Traffic separation schemes together with Vessel Traffic Services (VTS) improve existing safety standards within restricted areas. The VTS is any service designed to improve safety and efficiency of traffic and the protection of the environment. It may range from the provision of simple information messages to extensive management of traffic within a port or waterway [4]. Since the aim is clear one can suggest a possible development. It seems that the reference model presented in Figure 1 may contribute to easy interconnection. The model resembles that introduced by Horowitz [10] in order to control road traffic. The shore section of the model embraces supervisor or network management with traffic planning and a link layer. Its task is to overview and control traffic within a single segment. It also receives and discharges traffic flow from and to adjacent segments. The main task of the link layer is to send and receive

Table 1. Threat source and risk levels for various operating areas.

Operating area	Source of threat	Risk level
Port	Cargo handling	low
	Hazardous cargo handling	high
Restricted areas	Other vessels – collisions	high
	Shallow water and underwater obstacles – stranding	high
Ocean and open sea passage	Other vessels – collisions	low

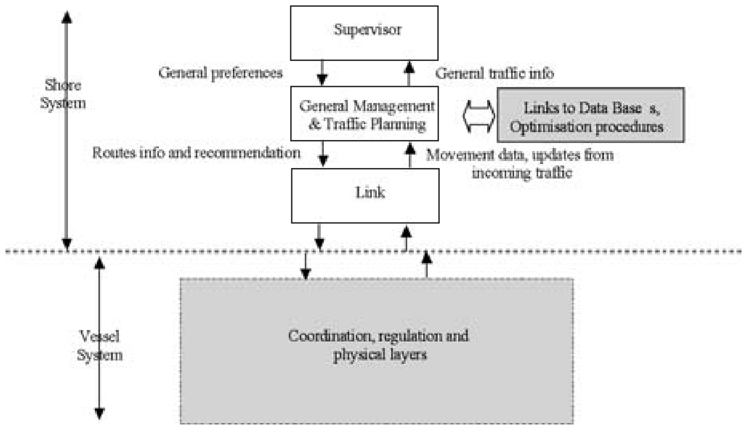

Figure 1. VTS architecture embraces both shore and vessel elements.

traffic data packets. There is one link layer for each segment of separation scheme. The link layer co-operates with the general management and traffic planning layer by regularly updating the passage plans. The plans are worked out based on results generated by optimisation procedures to solve control problems. The task of the supervisor or network layer is to control the whole system composed of isolated segments. The General Management and Traffic Planning layer of such a model was focused in a few papers delivered by the author [6][7][8]. Its role seems to be under-estimated and it is assumed that it will be crucial in terms of collision or accident risk reduction wherever implemented. Anderson and Lin [1] developed a collision risk model; the survey was done for the three dimensions involved in air traffic. Neglecting the vertical co-ordinate, the formula that reflects the probability of collision (p_c) at an intersection area is as follows:

$$p_c = f(\Theta)\varepsilon \quad (1)$$

It says that the probability of collision depends on the crossing area topology ($f(\Theta)$) as well as on an encounter rate (ε). An encounter is a situation involving the penetration of the domain area of any ship by another vessel. Any method of distributing the traffic that results in the avoidance of a local accumulation of ships should be considered vital in restricted areas since it would lead to a reduction in the number of encounters. This paper deals with the problem by aiming to reduce of the overall encounters for each vessel while passing through a restricted area.

The concept is 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

Table 2. Arbitrarily assigned set of safety factors.

Type of craft	Safety factor
Large and loaded tanker	10
Medium and loaded tanker	8
Small and loaded tanker	6
Large bulk carrier as well as medium general cargo vessel with dangerous cargo	5
Medium bulk carrier as well as small general cargo vessel with dangerous cargo	4
Ships without dangerous cargo	3
Others	1

within a sector at any time should not exceed a predefined capacity value. The particular route of a specific vessel will be associated with the cost value. The higher the cost, the less favourable the passage. The basic control problem is not to exceed the allowed capacities of sectors whilst maintaining a low overall cost.

2. BASIC CONCEPT.

The fundamental concept is based on zones of special care, first proposed by Goodwin and Richardson [9]. The concept was first exploited by the author in [6] and this paper extends the study. Such zones, called sectors, are those limited areas where it is considered necessary to control the movement of ships. The amount of traffic within a sector should be kept below the predefined level and is referred to as capacity. Every ship coming within the area has a safety factor 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. Arbitrary assigned safety factors are shown in Table 2. The sum of the safety factors describes the sector load. The sector's load, at any time, should not exceed its capacity. The assumption introduces a constraint to the problem. A passage timetable for all m vessels in a given sector is a vector of slots $P=\{P^i\}$ $(i \in \{1,2,3 \ldots m\})$. The time interval (slot) in which vessel S_k passes through sector is defined by:

$$P_{S_k}=[A_{S_k}, D_{S_k}] \tag{2}$$

where A_{S_k} is the arrival time at the sector and D_{S_k} the departure time from the sector of the S_kth vessel. Both values are rather more fuzzy than deterministic. Due to variation of speed and unforeseen deviation from the prescribed track, arrival and departure times change around an estimated value.

While ship S_k with the safety factor r_{S_k} is passing through the sector, its load is given by (3). This takes into account traffic which does not obey any rules. Disturbances identified as random variables could be defined for each period of time. The sector load is given by:

$$W_{S_k} = \max_{t \in P_{S_k}} \left(r_{S_k} + \sum_{l \neq k} (r_{S_l} \wedge (P_{S_k} \cap P_{S_l} \neq \emptyset)) + \eta_t \right) \qquad S_k,\ S_l \in \alpha \tag{3}$$

where η_t denotes interference expected at time t and α is a set of ships present inside the sector within the time slot, $\emptyset$ denotes an empty set. A graphical interpretation of (3)

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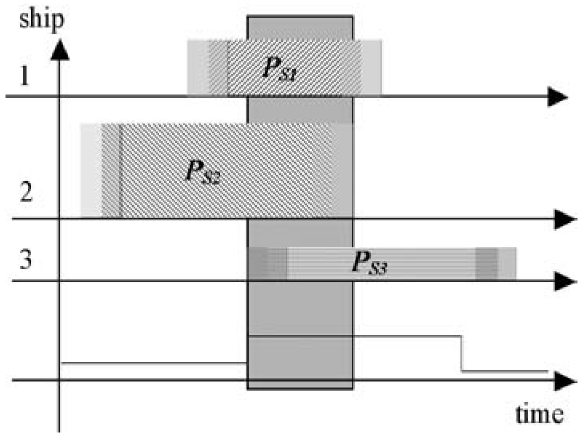

Figure 2. A sector's load is calculated using the sum of the ships' safety factors with overlapping slots; noise is also considered.

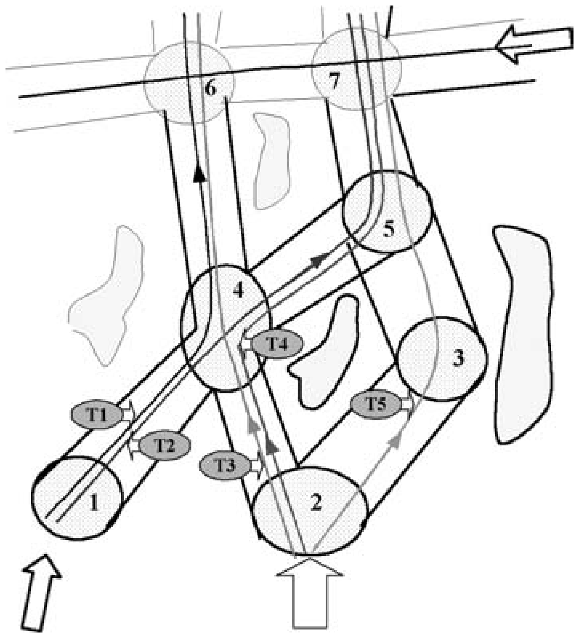

Figure 3. Example of restricted area with traffic separation and zones of special care.

is shown in Figure 2. The heights of the rectangular "slots" reflect the safety factors. The lowest part of the scheme represents noise as a part of the sector's load. The final aim for implementation of the scheme is to take over control of the ship after entering the controlled area. It is assumed that there is traffic separation within the area. The separation is to embrace new elements such as sectors and, possibly, alternative routes. An example of restricted area with traffic separation is shown in Figure 3. There are two main directions of flow with alternative routes for northbound vessels. The routes are labelled T1, T2, T3 and so on. The crossing and route junctions are treated as zones, or sectors, of special care. The possibility that one will be able to put special plug into a socket on the bridge and then watch what is going on seems remote. Many difficulties including standardization, legal and human factors need to be overcome. Any way of distributing ships which leads to avoidance of a local accumulation of vessels, should be beneficial in restricted areas with heavy traffic. It is expected that any solution aimed at reducing the overall encounters for each vessel passing through a given area is likely to be appreciated by seafarers. The most preferable condition from the Master's point of view is an uninterrupted, uneventful passage. This means that the vessel is free of any collision avoidance manoeuvres. The crew can concentrate on keeping to the prescribed track.

The introduction of the concept of sectors in a system of routes through an area, can be treated as a network with restrictions on the flow. The idea requires traffic to be reduced to the defined level. The sectors and buffers divide the area so that it can be treated as a network for which a wide variety of problems can be formulated. This concept creates an opportunity to adopt some of the published solutions devoted to stochastic networks. The Stochastic Multi-objective Shortest Path algorithm developed in [13][15] is a good candidate for an alternative routes environment where the best passage conditions are sought for a particular vessel. There is also a good opportunity to generalize the approach and to include vessel traffic control. The idea will be presented as single and multi-objective problems.

3. CONTROL PROBLEM.

A particular route by a specific vessel can be associated with its cost value. The higher the cost the less favourable is the passage. For example a fully loaded tanker steaming through a narrow channel, although possible, would be considered "costly". A higher cost value will be also assigned to any vessel that for any reason remains longer in the area than necessary. A shorter route is preferred to a longer one. Cost function C is related to the passage of ship S_k with the safety factor r_{S_k} along Tth route. In general: $C_{S_k,T}=f(r_{S_k}, M_T)$. This reflects local preferences (M_T factor) and depends on the type, length and cargo of the vessel as well as the depth and breath of the channels.

3.1. *Assumptions.* The graph structure of a system, R, in which nodes refer to the sectors. A set of vessels with a safety factor numbers assigned:

$$R=\{r_{S_k}\}\ (S_k \in \{1, 2, 3 \ldots n\})$$

The allowed sector load (capacity) B:

$$B=\{b_j\}\ (j \in \{1, 2, 3 \ldots m\})$$

The passage timetable P for given vessel:

$$P=\{P^i\}\ (i \in \{1, 2, 3 \ldots m\})$$

To adjust the load one can delay one or more vessels entering the sector. This can be achieved by slowing down at the adjacent buffer zone. Although such a measure is possible it will probably give rise to wide variety of complaints. The proposed approach is to adjust the load through a proper selection of routes while maintaining the speed unchanged. To fulfill that, the additional following assumptions are made:

- The route is treated as a sequence of adjacent nodes (sectors) characterized by a maximum load value for its nodes,
- To decrease the load in the given sector some vessels must be redirected along a different route. Two or more routes can be treated as the same from a given node point of view. In node 4 in Figure 3 at least two routes have the same predecessor – node 2.

The assumption reflecting the structure of a route can be expressed by the following formula, which considers the maximum allowable load of sectors as the route load:

$$W^T = \max_{i \in \beta^T;\ S_k \in \alpha_i} (W^i_{S_k} - b_i) \tag{4}$$

where β^T is a set of nodes of the Tth track. The load value of the ith sector $W^i_{S_k}$ is calculated from (3).

3.2. *Question of a Basic Decision Problem.* Is there such an assignment of routes for each of the vessels which does not exceed the capacity of sectors at any moment and the cost function is equal to a given value?

It was proved that such a problem belongs to the NP-complete class of the generalized allocation problems (GAP). A generalized assignment (or allocation) problem is a case of assigning a set of agents (ships) to a set of jobs (routes) where the cost of assigning each agent to any job is known. Each agent is assigned exactly one job and it consumes a certain amount of some resource to perform the job. The resource is related to each agent and is available as a limited quantity. Since the worst case running time of exact algorithms to solve such problem is exponentially bound, a wide variety of relaxation and decompositions can be proposed and adopted to obtain the solution within a polynomial time. The approaches and methods presented by Klastorin [11] are interesting. The effective subgradient method presented there inspired the author to work on algorithm for the current problem. Results are reported in the author's previous papers [5][7].

3.3. *PLA Methods.* Metaheuristcs or extended heuristics are growing in popularity nowadays. These algorithms require powerful computers to obtain a solution close to an optimal value within a reasonable time. They are also able to produce a satisfactory outcome when run on standard PCs. Population Learning Algorithms (PLA) are those emerging extended heuristics that bring a new approach towards the computational technique. PLAs reflect the idea that lies behind social education systems. They are based on the evolution of populations of individuals. The computation scheme enables the combination of different optimization techniques. Just as in a normal education system, PLAs start with basic level training applied to randomly selected individuals. Those that pass the necessary tests and satisfy promotion criteria are promoted. Subsequent stages involve more sophisticated methods of education and more difficult selection criteria. 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. These education scenarios play an important role in PLA computations. Carefully selected and implemented, they can bring the expected result within a reasonable time, but choice of a "first to fit" scenario can result in an unacceptable outcome. In this respect the scenarios need to be treated as problem oriented.

Table 3. Summary of the Computational Results.

Routes	Ships	Optimal value (max.)	Result	Percentage deviation [%]
5	15	326	326	Optimum
5	25	564	564	Optimum
8	24	559	558	0·18
8	24	568	568	Optimum
10	60	1446	1444	0·14
10	60	1451	1447	0·28

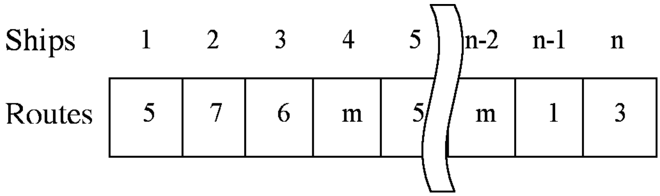

Figure 4. Representation of a PLA individual is very much the same as in Genetic Algorithms.

The basic characteristics of the PLA methods are as follows:

- Scenario is an important factor in computation.
- Stage-by-stage or continuous calculations can be carried out.
- The method is inherently suited towards parallel processing run on multi-processor or multi-computer systems.
- Flexibility of the computation schemes is achieved by exploiting the idea of dynamic link libraries.
- Properly designed and maintained libraries can result in a powerful and universal computation environment.

PLAs work with individuals much like other genetic algorithms [2]. An individual in the current problem is a vector of integer numbers illustrated in Figure 4. An appropriate representation of an individual is important and it should be liable to crossover, mutation and other problem-specific operators [12]. In the vector representation the integer numbers identify the ships as assigned to routes. In the figure ship 1 is assumed to pass through route 5, ship 2 is assigned to route 7, ship 3 to route 6, and so on. This representation ensures that each vessel is assigned to a single route.

To generate an individual, one has to randomly assign a route to each ship. Such a simple procedure is likely to create an assignment that violates the capacity constraint [4]. After passing a capacity violation test such individuals usually emerge as the initial population designated for further processing.

Selected computational results are shown in Table 3. Experiments were carried out for various numbers of single sector routes and ships. Sector capacities as well as vessel safety factors were randomly generated figures. To match the results obtained against a valid optimal value the goal function was reversed to maximization. This creates a bit of awkward reality but does not jeopardize the quality of results or the correctness of the approach. The results seem good even for very demanding tasks. It is worth stressing that the output has been achieved with the use of an extra tuning stage in the computation, this idea was suggested in [2]. The basic applied scenario

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consisted of generation of initial population, a wide variety of mutation and then crossover. The outcome of such a simplified approach differed from optimal values by around 5–6%. The fine-tuning stage was focused on the improvement of the created individuals. Each individual was tested for resource constraints and if they failed attempts were made to find a better route. Finally, for each ship a search was conducted to find a less costly route with a sufficient load margin.

4. MULTI-OBJECTIVE APPROACH. The approach used in section 3 solves the route allocation problem using a population learning evolutionary algorithm. It has also been shown [7][11] that Lagrangian relaxation might be successfully adopted for this task. The approach is single objective and the goal is to minimize the overall cost function. Such an objective applied to a network of limited capacity sectors enables distribution of the traffic within the area. Preliminary simulation results have proved that this contributes to a dramatic reduction of the total encounter number.

However, most real problems are multi-objective ones with many criteria. To satisfy each of them simultaneously is usually impossible since they are often conflicting. In the problem under discussion, as well as minimizing the overall cost function the decision maker can also be interested in the situation within a particular area or in the route of a particular vessel. The objective should additionally penalize encounters with craft with a high safety factor. Extra penalties might be applied if too many vessels are gathered in an area of special concern containing several sectors. In other words each allocation of routes is subject to a variety of assessments. These criteria need to be minimized to solve the multi-objective problem. The ships' routing analysis can therefore be based on the following criteria:

- minimizing overall cost function,
- reducing the number of encounters for a particular vessel,
- reducing the number of ships present in an area of special concern (particular set of sectors and surrounding waters) from the local authority point of view,
- minimizing maximal load of a sector,
- minimizing "chaos" in the adjacent area, in order to perform a passage plan some ships are to be redirected from their intended routes. This is likely to create additional encounters, which should not be neglected.

Evolutionary algorithms are particularly suitable to solve such multi-objective problems [3]. Such algorithms deal with individuals within a population and this allows for verification over a wide scope of criteria.

Individuals that improve any of the goal functions comprise the 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 [15]. Contrary to a single criteria approach the set contains more then one vector of decision variables. Such a set contains allocations, which represent available tradeoffs. As an example consider three allocations with the parameters presented in Table 4. The data presented in the columns are:

- allocation number,
- calculated cost function,
- number of encounters involving ships with a safety factor greater than 4,

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Table 4. Comparison of Route Allocations.

Allocation	Overall cost	Encounters with SF > 4 involved	Encounters within area X with SF > 4 involved	Max. load	Outside crossings	Dominance
1	350	5	3	80%	4	Dominated by 3
2	330	6	3	79%	3	Non-dominated (neither by 1 nor by 3)
3	325	5	2	80%	3	Dominates 1 but does not dominate 2

- number of encounters involving ships with safety factor greater than 4 and which occurred in the area of special concern,
- maximal, relative (load/capacity) sector load,
- number of crossings that occurred in the adjacent area related to executing a given routing schedule.

It can be seen that solution number 3 dominates allocation number 1 since it has a lower overall cost and is not worse in any other criteria. The Pareto optimal set solution 1 is to be neglected. Allocation 2 is dominated neither by 1 nor by 3.

5. SUMMARY AND CONCLUSIONS.

The idea of sectors, as areas of special care, enables the formulation of control problems. It introduces constraints that contribute to traffic distribution over the area. Provided alternative routes exist one can formulate and solve the route allocation problem. The problem belongs to a family of generalized assignment problems. It aims at the assignment of routes for each vessel to bring down the cost value and avoids any violation of the imposed constraints. If the cost function awards the shortest passages then the solution reduces the overall encounter numbers and maintains order in the area outside the traffic separation.

A closer look at the problem justifies the idea of a multi-objective approach. Real world situations show that special care must be attached to a particular vessel or a particular set of sectors with surrounding waters. For this reason the set of goal functions should be considered open to the addition of new ones.

The multi-objective approach usually involves 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 alternatives, presumably the best, present in the Pareto optimal set. There are many methods available that can be readily used. The simplest approach, see [3], is to combine objectives into a single function. Usually each objective receives its weight and the function is a polynomial, from which the minimal (maximal) value is sought. Use of the multiple attribute utility theory enables the creation of functions to order solutions from best to worst. The method can be adopted for all occasions where comparable criteria are to be taken into account. However, the method cannot be used if the criteria are incomparable. One cannot compare total cost function (in units of time) with the load of sector (relative measure given as a consumed percentage of total capacity). Other approaches are needed for such cases and ranking methods have been developed to cope with these conditions. Current work is being directed to the final stage of adaptation and incorporation of these ranking methods into the problem. The solutions and final decisions will be incorporated into the Passage Planning and Optimization layer of the VTS reference model.

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