Dynamic Group Transit Scheme for Corridor Transit

Ondřej Vaněk, Michal Pěchouček
Department of Computer Science and Engineering, Faculty of Electrical Engineering, Czech Technical University
Karlovo Náměstí 13, Praha 2, 127 00, Czech Republic
Email: {name.surname}@agents.fel.cvut.cz

***Abstract*—Contemporary maritime piracy around the Horn of Africa presents a serious threat to the global shipping industry. A number of countermeasures were deployed to minimize the probability of a successful hijack, one of them being the establishment of the International Recommended Transit Corridor (IRTC). Currently, all ships transiting the Gulf of Aden are strongly recommended to follow the IRTC and take part in group transit schemes—prescribed schedules stating time of arrival to the beginning of the corridor and speed at which to sail through the corridor. These schedules are fixed in advance and do not take into account speeds and constraints of arriving ships.**

We propose dynamic grouping schemes, customized schedules for a group of arriving ships, which take into account speeds as well as positions of arriving ships. The problem of finding optimum grouping scheme for a group of arriving ships is formulated as a bi-objective mixed integer program, weighting the delay caused by the grouping scheme and the risk taken when sailing alone. We look for a set of Pareto optimal solutions and compare the dynamic grouping scheme with currently deployed fixed scheme. Results show an improvement over current grouping scheme with respect to the number of ships grouped as well as time saved.

***Keywords*—Mathematical programming, Pareto optimization, Marine navigation, Security**

I. Introduction

Contemporary maritime piracy presents a serious threat to global shipping industry with its annual total costs estimated at up to US$7bn [1]. Recent spike of piracy in the Indian Ocean and in the Gulf of Aden required an international response in form of international naval forces deployed in the area. They provide protection to the transiting merchant ships and their presence significantly reduces the success rate of pirate attacks. To provide best protection of merchant ships possible, International Recommended Transit Corridor (IRTC) was established in the Gulf of Aden which aligns ships along a single lane and a *group transit scheme* was proposed to group ships inside the corridor to groups with a predefined speed for easier escort with limited number of patrolling naval ships.

Current group transit scheme is defined by 5 speed levels—creating groups transiting the corridor at speeds of 10, 12, 14, 16 and 18 knots—and by specific hours at which the group leaves from each entry point of the corridor. To participate in the group transit, a ship slows down to the closest predefined speed level; ships sailing faster that 20 knots are recommended to sail at their full speed without participating in the grouping scheme. One group per speed level is formed every day at a predefined hour at both ends of the corridor; groups are disbanded after the corridor transit. The times are prescribed such that groups sailing at different speeds are close to each other in the most dangerous area at night and leave the most dangerous area at dusk together. The scheme thus groups the ships into groups and additionally also aggregates the groups together.

The grouping mechanism is—while reducing probability of a successful attack—causing significant delay: ships participating in the group transit have to slow down prior the corridor transit to arrive at the beginning of the corridor at the predefined hour and then they have to sail at the speed of the group. This delay can be directly translated into increased costs of shipping. Additionally, as the current grouping mechanism does not take into account specific positions and speeds of ships arriving each day, some ships can arrive at the beginning of the corridor at the designated time alone and are thus forced to sail without any advantage of being in a group.

The contribution of this work is a design of a dynamic grouping mechanism for a set of approaching ships based on dynamic group creation rather than on a fixed schedule, minimizing both delay caused by the grouping scheme and risk of transiting the corridor alone. We formalize the problem of dynamic grouping of approaching ships as a constrained aggregation of spatially distributed agents along a line and we propose a bi-objective mixed integer linear program weighting the delay caused by the grouping scheme and the risk taken when sailing alone. We look for a set of Pareto optimal solutions and explore the structure of the solution and the scalability of the algorithm. When comparing the computed solutions with the currently deployed fixed grouping scheme, the results show an improvement over current grouping scheme with respect to the number of ships grouped as well as time saved.

The paper is structured as follows: Section II summarizes related work on the subject, Section III describes the situation and the grouping scheme in detail, Section IV describes the formalization and the solution approach, and Section V finally focuses on properties of the algorithm as well as the comparison with the current fixed grouping scheme.

II. Related Work

Current group transit scheme, together with description of the International Recommended Transit Corridor, is well explained by Intertanko [2]; however, the original computation of the currently used times and speeds for groups is not described—to our best knowledge—in any of the public sources. Hrstka and Vaněk [3] derive a formal model of this problem and design an algorithm able to compute optimal fixed schedules (i.e. times and speeds for given number of groups) for a given dataset of ships' speeds.

Dynamic grouping is a new paradigm not deployed for

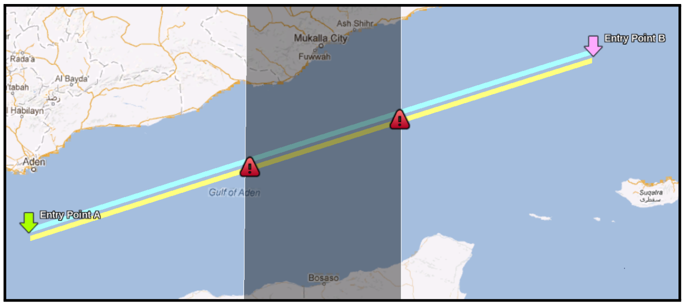


Fig. 1. IRTC Corridor in the Gulf of Aden. Ships enter the gulf area from both sides. The most dangerous area is in the middle (denoted by the dark zone) and it is best to be crossed at night; entering and exiting this area is the most dangerous part of transit as most attacks take place at dawn/dusk.

the IRTC transit and—due to its specific set of constraints—no model is directly applicable to the problem. Two problem sets are related to some extent: Grouped Sweeping Scheduling (GSS) and Convoy Movement Problem (CMP). In the GSS [4], [5]—frequently used in multimedia storage management—the problem is to minimize a buffer space in retrieval of heterogeneous multimedia streams by dividing set of streams into groups, subject to a set of constraints posed by the physical architecture of the disk. The approach differs from our work, as the criteria and constraints posed on actors participating in the grouping are different.

In the CMP [6], [7], the problem is to minimize total movement time of a set of convoys moving in a directed graph, subject to a set of following constraints: the convoys do not stop en-route (same requirement), they do not cross each other, they have the same speed and they are ready for transport at time zero. In our case, the groups have different speeds, can cross each other and have to react prior the transit.

III. Problem Description

Gulf of Aden is a narrow area north from the coast of Somalia with dense merchant traffic in both directions, mostly transporting goods and oil from Asia to Europe. Current spike in Somali-based piracy poses a serious threat to merchant ships transiting the area of the Indian Ocean and the Gulf of Aden—hundreds of hijack attempts were reported from 2008 till today and tens of ships were hijacked every year [1].

A. International Recommended Transit Corridor

International naval forces were deployed in the area to protect the merchant ships and International Recommended Transit Corridor (IRTC) was established to align the traffic into a two lanes—separating East bound and West bound traffic—for easier protection (see Figure 1). The IRTC East bound lane begins at 45°East between 11°48’ North and 11°53’ North. The lane is oriented along a straight line course of 72 degrees and terminates at 53°East between 14°18’ North and 14°23’ North. The IRTC West bound lane begins at 53°East between 14°25’ North and 14°30’ North. The lane is oriented along a straight line course of 252 degrees and terminates at 45°East between 11°55’ North and 12°00’ North. The width of each lane is 5 nautical miles and the lanes are separated by a 2 nautical miles wide buffer zone [2].

TABLE I. Gulf of Aden group transit schedule.

Speed	Entry A	Entry B
10 kn	04:00	18:00
12 kn	08:30	00:01
14 kn	11:30	04:00
16 kn	14:00	08:30
18 kn	16:00	10:00

B. Group Transit Scheme

In August 2010, a group transit scheme was introduced to further reduce the risk of pirate attacks [8], [9]. Gulf of Aden Group Transits are designed to group ships into different speed groups in order to exploit additional protection and assurance of traveling in a group. Each transit follows a designated lane in the IRTC at a published speed that avoids highest-risk piracy areas and time intervals and allows maximum effectiveness of supporting military assets if needed. There is one transit per day for each speed group (shown in the Table I).

The times for different speed groups to enter the IRTC are calculated so that the groups pass through the most dangerous area, between 47°East and 49°East (depicted on Figure 1), at night and they ensure that all ships, regardless of speed, are together at dawn. The group transit scheme thus groups the ships on two tiers: first, the ships are grouped according to their speed and second, the groups are grouped again at the most dangerous area in the Gulf of Aden to transit the area together. This allows the military forces to best position their assets in the area so as to protect ships against piracy and to provide assistance in case of attack.

Analysis of successful and attempted pirate attacks in the region clearly indicates that attacks during darkness are rare and, to date, have zero success rate. Many of the successful attacks have occurred around first or last light in the area between 47°East and 49°East. Statistics for years 2010-2012 show that there were very few successful attacks on ships following group transit times and speeds[1].

C. Motivation for Dynamic Group Transit

Even though the group transit scheme aggregates the traffic and lowers the hijack probability, it can be further optimized to take into account following facts: (1) The grouping scheme is *fixed*, i.e. it does not take into account speeds of actual ships arriving into the Gulf. For these ships, a dynamic grouping scheme can be designed, which adheres to the constraints given by the second tier grouping (i.e. all groups should transit the most dangerous area together) and minimizes the delay caused by the grouping scheme only for the arriving vessels, better taking into account their speeds; additionally, it should also lower the probability of a ship being left out of the grouping mechanism. (2) Current group transit scheme does not take into account the risk aversion of individual ships, i.e. if a ship has invested into counter-piracy measures and she is well protected against any attack, it is shouldn’t be mandatory to take part in the group transit (and vice versa).

IV. Optimization Problem

In the dynamic group transit problem, we have to take into account not only speed of the approaching ships, however, also

[1] http://www.icc-ccs.org/piracy-reporting-centre

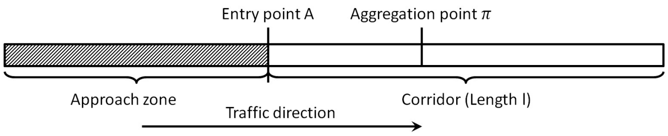


Fig. 2. Schematic visualization of the dynamic group transit setting.

their positions with respect to other ships as well. Additionally, we have to deal with a (possibly infinite) stream of approaching ships transiting IRTC. The latter issue can be solved in two ways: (1) design an algorithm which continuously creates groups and adds ships on the fly (using, e.g., rolling horizon approach) or (2) cluster approaching ships into clusters and compute group transit for each cluster. We will focus on the latter approach, because of the specifics of the Gulf of Aden transit: typically, vast majority of the ships arrive from or continue its journey to the Strait of Suez. Strait of Suez employs its own traffic system, structuring all ships transiting the strait into groups which transit the strait once per day[2]. This means, that the daily transit of ships through the Strait of Suez forms a cluster for which we design the dynamic grouping scheme.

A. Abstraction

Figure 2 depicts the abstraction of the environment for the group transit formation: the ships transit the area from left to right, reaching the *approach zone* first. Only the ships in the approach zone are considered for grouping[3]. The groups are established at the Entry point A and they follow the corridor (of a fixed length l). Additionally, inside the corridor, there is an *aggregation point* π, in which all the groups have to meet. Moreover, the aggregation point has a specific time of the day U assigned, at which the groups have to be at the point. Note that the last two conditions place additional constraints on the problem and can be relaxed in similar models without such requirements.

To express the advantage of a ship being in a group, we use a term *risk*. If a ship does not take part in the group transit, it is facing an increased risk of hijack, because it does not obey the required time of transit of the most dangerous area or it does not sail at the recommended group speed (or both). We express this increased risk as a parameter: if the ship is in a group, there is no increased risk; if the ship is not in any group, it is subject to an increased risk expressed by a *risk aversion* $R_j \in [0, 1]$ parameter, set individually for each ship. For $R_j = 0$, the ship does not gain anything by being in a group, for $R_j = 1$, the ship suffers maximum penalty for being left out of the grouping scheme.

B. Mathematical Model

The parameters and notation used throughout the section are summarized in the Table II. We formulate the problem of dynamic group transit as a bi-objective optimization problem

TABLE II. NOTATION USED IN MATHEMATICAL MODEL OF THE DYNAMIC GROUPING SCHEME.

Notation	Notation
$s \in \mathbb{N}$	number of speed levels
$n \in \mathbb{N}$	number of ships in the approach zone
Π (GPS)	coordinates of the aggregation point π
$u \in \mathbb{R}^+$	time of the day when the groups have to be in π
$\nu \in \mathbb{R}^+$	minimum approach speed of any ship
$\mu \in \mathbb{N}$	minimum group size
$\tau \in \mathbb{R}^+$	current time
$\Delta V \in \mathbb{R}^+$	maximum allowed speed difference in one group
A (GPS)	coordinates of the entry point
$P \in \mathbb{R}^n$	position of ships (P_j is position of j-th ship)
$V \in \mathbb{R}^n$	speed of ships (V_j is speed if j-th ship)
$T \in \mathbb{R}^n$	the earliest time the ship can arrive to the entry point A (for j-th ship, the value is computed as: $T_j = \lvert P_j - A \rvert / V_j$)
$R \in [0, 1]^n$	The risk value expresses the risk aversion of a ship (R_j is risk of j-th ship)
$U \in \mathbb{R}^m$	vector of admissible days to be at the aggregation point Π w.r.t. the minimum approach speed ν
$L \in \mathbb{R}^+$	length of the corridor

with two objective functions: $delay$ and $risk$, which are subject to a set of constraints on the schedule properties and ship abilities:

$$\min \quad (delay(x), risk(x)) \tag{1}$$
$$\text{s.t.} \quad x \in X \tag{2}$$

where X is a set of feasible solutions defined by constraints. We scalarize the multi-objective criterion into a single weighted linear combination of the two functions:

$$\min \quad D + \gamma \cdot \mathcal{R} \tag{3}$$

where the delay function D has two components $D = D_a + D_t$, where D_a is the delay caused lower speed of the ships in the approach zone and D_t is the delay caused by lower speeds of grouped ships when transiting the corridor. $\mathcal{R}$ is the overall risk aggregated over all ships. The solution is not unique due to the counter-going objective functions, as delay and risk are inversely proportional; we thus look for a set of Pareto-optimal solutions – i.e. the Pareto front – by varying the γ parameter.

We define the terms in the criterion 3 as:

$$D_a = \sum_{j \in n} \omega_j \tag{4}$$
$$D_t = \sum_{i} \sum_{j \in n} \sum_{k \in m} U_k \cdot y_{ijk} \tag{5}$$
$$\mathcal{R} = \sum_{j \in n} R_j \cdot (1 - \sum_{i \in s} x_{ij}) \tag{6}$$

where ω_j is the entry time of j-th ship at the entry point A (capturing the approach delay D_a), y_{ijk} is a variable indicating that j-th ship in the i-th group would sail through the aggregation point Π at time U_k (capturing the transit delay D_t). The equation (6) expresses the risk as a sum of individual risks of all ships which are not assigned to any group (variable x_{ij} indicates that j-th ship is assigned to i-th group and the expression $(1 - \sum_{i \in s} x_{ij})$ is 1 if and only if j-th ship is not assigned to any group).

Criterion 3 is optimized subject to a number of constraints capturing structure of the grouping mechanism. First, we

[2]For details, see Strait of Suez Traffic System website: http://www.suezcanal.gov.eg/sc.aspx?show=13.

[3]Note that the size of the approach zone determines the number of ships for the group transit scheme computation and its size has a significant impact on the size of the problem (and thus on the ability to compute the optimal solution).

impose a set of constraints for a correct grouping, expressed as:

$$\sum_{i \in s} x_{ij} \leq 1 \qquad \forall j \in n \qquad (7)$$

$$\sum_{j \in n} x_{ij} \geq \mu - M \cdot a_i \qquad \forall i \in s \qquad (8)$$

$$\sum_{j \in n} x_{ij} \leq 0 + M \cdot (1 - a_i) \qquad \forall i \in s \qquad (9)$$

$$x_{ij} \in \{0, 1\} \qquad a_i \in \{0, 1\}$$

Constraint (7) specifies, that each ship can be at most in one group, Constraint (8) restricts the group size to be greater than or equal to a pre-specified minimum group size μ and Constraint (9) allows the group to be of size 0 (thus having no ship assigned). The binary variable a_i indicates that only Constraint (8) or (9) can be active at the same time for i-th group and M is a large number.

To capture properties of group formation at the entry point A, we introduce variable w_i capturing entry time of i-th group with the following constraints:

$$\omega_j \geq w_i - M(1 - x_{ij}) \qquad \forall i \in s; \forall j \in n \quad (10)$$

$$w_i \geq -(1 - x_{ij}) \cdot M + \tau + T_j \qquad \forall i \in s; \forall j \in n \quad (11)$$

$$w_i \leq (1 - x_{ij}) \cdot M + \tau + \frac{|P_j - A|}{\nu} \qquad \forall i \in s; \forall j \in n \quad (12)$$

$$w_i \in \mathbb{R}^+ \qquad \omega_j \in \mathbb{R}^+$$

Constraint (10) links the entry time of j-th ship to i-th group, i.e., if the j-th ship is in the i-th group, then (due to the minimization criterion) $\omega_j = w_i$. Constraint (11) expresses the fact, that the group cannot be established at the entry point A earlier than every ship reaches the entry point A (relative to the current time τ), posing a lower bound restriction on w_i. Constraint (12) poses an upper bound restriction on w_i by assuring that no ship violates the minimum approach speed requirement (given by ν)[4].

Finally, we incorporate the restriction given by the necessity to aggregate the groups at the aggregation point π:

$$\sum_{k \in m} y_{ijk} \cdot U_k - w_i \geq \frac{|\Pi - A|}{V_j} \cdot x_{ij} \qquad \forall i \in s; \forall j \in n \quad (13)$$

$$\sum_{k \in m} y_{ijk} \cdot U_k - w_i \leq \frac{|\Pi - A|}{V_j - \Delta V} + M \cdot (1 - x_{ij}) \qquad \forall i \in s; \forall j \in n \quad (14)$$

$$\sum_{k \in m} y_{ijk} = 1 \qquad \forall i \in s; \forall j \in n \qquad (15)$$

$$y_{ijk} \in \{0, 1\}$$

As stated, variable y_{ijk} indicates that the j-th ship in i-th group will be present at the aggregation point Π on day U_k (at given time u). Constraint (13) states that the speed of a group cannot exceed the speed of any ship which belongs to this group (i.e. the time needed for a group to reach Π is given by $\sum_{k \in m} y_{ijk} \cdot U_k - w_i$ and the time needed for a ship to reach Π is given by $|\Pi - A|/S_j$). Constraint (14) restricts the spread of the speeds of ships in one group to be at most ΔV. Constraint (15) states that only one time of passing Π is admissible for any group.

The equations above fully capture the problem, however, we can add additional redundant constraints to speed-up the solution process:

$$x_{ij} \neq x_{il} \quad \text{iff} \quad |V_j - V_l| > 2 \cdot \Delta V \qquad \forall i \in s; j, l \in n; j \neq l \quad (16)$$

$$x_{ij} \neq x_{il} \quad \text{iff} \quad et_j > lt_l \quad \text{OR} \quad et_l > lt_j \qquad \forall i \in s; j, l \in n; j \neq l \quad (17)$$

i.e. no two ships can be in one group, if the difference of their speed is greater than $2 \cdot \Delta V$ and no two ships can be in one group if the earliest time et_j of one ship to arrive to A is greater than the latest time lt_l when the other ship has to leave A (given by the minimum approach speed requirement) or vice versa. The times are computed as $et_j = dist(P_j, A)/s_j$ and $lt_j = dist(P_j, A)/\nu$, where $dist(P_j, A)$ is orthodromic shortest path between P_j and A.

Having the full problem formulation, we can relax or restrict any of the constraints to customize the grouping scheme. Following variations have been considered by the authors:

Mandatory grouping—we modify Constraint (7) to account for a mandatory assignment of every ship into any group, i.e. $\sum_{i \in s} x_{ij} = 1$. Having this restriction, the risk summand in the criterion function is redundant and can be left out. However, note that the problem cannot be always feasible, due to the requirements of the minimum approach speed (Constraint (12)) and maximum speed difference in one group (Constraint (14)). These constraints have to be either relaxed or the program has to be solved multiple times while decreasing the minimum allowed approach speed ν and/or increasing maximum speed difference ΔV.

Group size limit—we can additionally limit the size of the group to be at most η[5] by introducing a constraint $\sum_{j \in n} x_{ij} \leq \eta$. In this case, the number of groups should be proportionally increased to create enough groups and not to be penalized for the risk of ships that cannot be placed in any group because of this constraint.

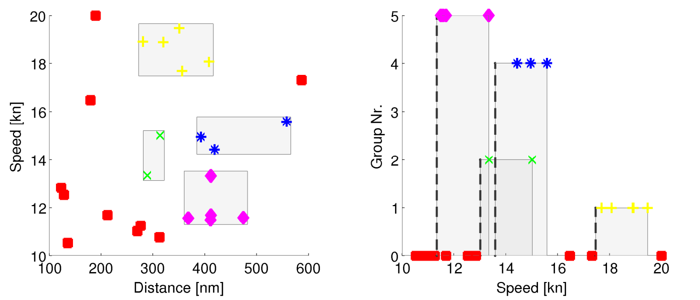
It is further possible to consider grouping schemes without aggregation point Π and/or without the approach buffer (i.e. the groups are assembled directly at the entry point A). As these schemes modify the formulation above significantly, due to space requirements, they are out of scope of this paper.

V. Evaluation

We first look at the structure of the optimal dynamic group transit. We further explore the Pareto frontier and evaluate the scalability of the algorithm with respect to main algorithm parameters. Finally, we compare the dynamic group transit to the currently deployed fixed schedule. The tests were executed

[4] Note that it is trivial to account for different minimum approach speeds for each ship. For each ship, we can introduce ν_j variable and directly use it in constraint (12).

[5] Where $\eta \geq \mu$. Note that when setting the $\eta = \mu$ we get groups of the exact size.



(a) (b)

Fig. 3. Structure of the solution. Grouping for $n = 25$ ships and $s = 4$ groups. Note that slow ships close to the entry point A are rarely grouped. Compared to the fixed grouping schemes, the group speeds are not uniformly distributed and ships of similar speed can be grouped into two different groups.

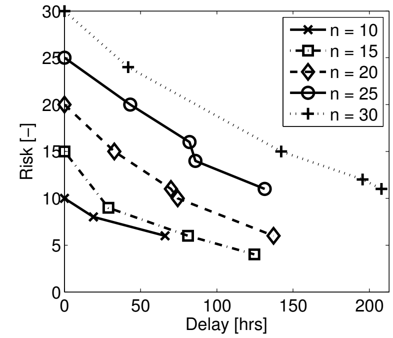


Fig. 4. Pareto frontiers for number of ships $n = \{10, 15, 20, 25, 30\}$. As we increase risk aversion coefficient γ, the risk is lower with the tradeoff of an increased delay. Note that solutions which are not Pareto efficient would lie *above* the curve, as the criterion is minimized.

on a 2.8GHz Quad-core 64-bit PC with 4GB available RAM, implementation was done in Java 1.7 and we used CPLEX 12.3 to solve the mathematical programs.

We generate synthetic scenarios where ships are spread uniformly in the approach zone which should imitate the hardest possible conditions (i.e. the worst case) for successful grouping. Note that in real-world, the ships would be often significantly clustered and will be grouped farther from the entry point A, thus the solutions would be significantly better (in terms of number of ships grouped). We generate ship speeds from a uniform distribution, again emulating worst case possible. If not stated otherwise, tested values of parameters are set by default to: number of ships $n = 25$, number of groups $s = 5$, minimum approach speed $\nu = 8$, maximum speed difference in a group $\Delta V = 2$ and minimum group size $\mu = 2$.

A. Structure of the Solution

The structure of a solution is demonstrated on one scenario with a high risk weight $\gamma = 1000$, $n = 25$ ships and $s = 4$ groups. Figure 3a captures the distribution of groups in two dimensions: distance of a ship to the entry point A and speed of an individual ship, Figure 3b additionally accents speed of each group. We can observe that some ships are left ungrouped (red squares in plots). These ships are either slow or very close to the entry point A and cannot slow down too much to meet the minimum approach speed constraint. Note (Figure 3b) that some groups in the solution have lower group speed than the speed of the slowest ship in the group. This is caused by the restriction of a specific set of times of arrival at the aggregation point Π.

B. Pareto Frontier Evaluation

In the optimization problem defined by criterion (3), we weigh two functions through a parameter γ. While varying γ, we obtain different solutions with different risk and delay caused by the grouping scheme. Figure 4 captures the Pareto frontiers for default parameter values, individual risk set to $R_j = 1$ for each ship and for $n = \{10, 15, 20, 25, 30\}$ ships. Every point on the the graph represents a solution in form of the sum of approach and transit delays of all ships (x-axis) and the risk summed over all ungrouped ships (y-axis). The Pareto frontier curves are almost linear, with non-smooth transitions due to the binary property of group membership. Scalability of algorithms with respect to γ is described in next Section.

C. Scalability

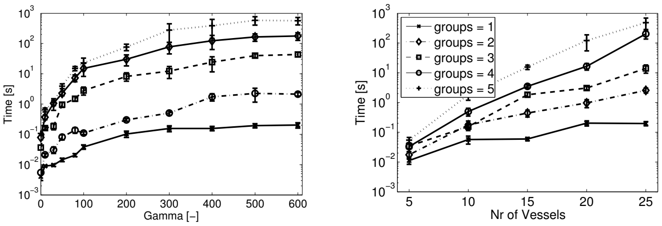
The performance of the algorithm depends on number of parameters: number of ships, number of groups, risk aversion coefficient, maximum speed difference in one group, minimum approach speed of any ship and minimum group size. Here we focus on the first three parameters as they have the greatest impact on the speed of the algorithm. We have generated 100 random instances of the problem for each parameter setting and averaged the computation time needed to find a solution.

The scalability of the algorithms with respect to the risk weight coefficient γ is captured in Figure 5a. We varied γ from 0 to 600 for a setting with $n = 25$ ships and $s = 1, 2, 3, 4, 5$ groups, while having all other parameters fixed at default values. Note that for larger risk weights (i.e. $\gamma > 600$), the time needed to find a solution does not increase significantly, as the risk summand in the criterion outweigh the delay summand and if a ship can be grouped, the algorithm places the ship in a group. As expected, the time needed to find solutions grows proportionately to the number of groups.

The dependency of solution time on the number of ships and number of groups is depicted in Figure 5b. We are able to find solutions for up to $n = 25$ ships and $s = 5$ groups under 10 minutes in average. When increasing the number of ships or number of groups over these values, most of the problem instances are solvable in hundreds of minutes; however, some problem instances are not possible to solve within 4GB of RAM. The maximum solvable problem size is thus heavily dependent on the memory efficiency of the solver.

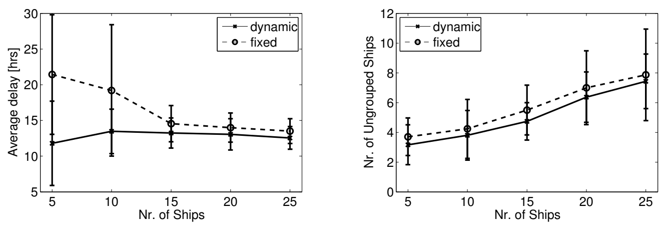
D. Comparison with Fixed Schedules

To compare the dynamic group transit with fixed group transit schedules, we measured the delay caused by both grouping schemes and the number of ships left ungrouped (by either not satisfying the minimum approach speed constraint or—in case of the fixed schedule—being alone in the group) for both the grouping schemes. We have set minimum approach speed $\nu = 8$ for both schemes. For dynamic grouping scheme, we have set the risk weight coefficient to $\gamma = 1000$ (to force



(a) (b)

Fig. 5. Scalability of the algorithm. (a) Scalability of the algorithm with respect to risk weight coefficient γ. (b) Scalability of algorithm while modifying number of ships and number of groups. The error bars depict standard error.



(a) (b)

Fig. 6. Comparison of fixed and dynamic grouping schemes. (a) Comparison of delays caused by the currently deployed fixed grouping scheme and by the dynamic grouping scheme (lower is better); (b) comparison of number of ungrouped ships for fixed and dynamic grouping schemes (lower is better).

maximum grouping with possibly increased delay), number of groups to be created to $s = 5$ and maximum speed difference in one group to $\Delta V = 2$ to be equal the currently deployed fixed grouping scheme. We have varied the number of approaching ships from 5 to 25 and run 100 samples for each setting.

The results are depicted in Figure 6. We can observe, that the delay caused by the dynamic group transit is lower than the delay caused by the fixed grouping scheme for less ships, however, as the number of approaching ships increases, the delays caused by both groupings are comparable, as all groups are filled due to the constraints imposed by the aggregation point Π—the slightly better performance of the dynamic grouping is given by proposal of speed levels which take into account individual speeds of approaching ships[6]. Observe rather high standard deviation for 5 and 10 ships which is caused by a low number of groups created. In many cases, there is only a single group; for a single group, the delay can be either high or low, depending on the speed level of the group. For a higher number of ships, a higher number of groups is created and the delay averages out over all speed levels of all the groups.

In Figure 6b we can compare the average number of ungrouped ships for both schemes. Dynamic grouping scheme has steadily lower number of ungrouped ships (which is preferable). For high number of ships, the ungrouped ships typical don't meet the minimum approach speed requirement.

[6]As shown in [3], the speed levels of current fixed schedule are not far from the optimum fixed schedule with the same number of speed levels so no significant advantage can be reached in this aspect.

VI. Conclusions

One of the current countermeasures deployed to minimize the risk of a pirate attack in the Gulf of Aden is the establishment of the International Recommended Transit Corridor with group transit schedules aligning transiting merchant ships into groups with a number of speed levels. The current fixed grouping scheme has a number of disadvantages because it does not take into account properties of ships arriving every day.

We design a bi-objective mixed integer linear program able to find optimal groupings for a set of approaching ships while adhering to constraints posed by the original grouping mechanism. The criterion function balances the trade-off between delay caused by the grouping and risk taken by the ungrouped ships. We show that under the current constraint set, containing both the aggregation point inside the corridor and the approach buffer, the algorithm will primarily group ships further from the corridor entry point. We show that – compared to the current fixed group transit scheme – our approach is superior both in number of ships grouped as well as in time saved. The scalability of the mathematical program is limited, scaling up to 30 ships and 6 groups, memory being the main bottleneck. This limitation could be elevated by use of heuristic solution methods which are subject to current research. However, to evaluate degree of sub-optimality of such methods, a reference optimum approach – such as the one described in this paper – is essential.

Acknowledgements

Funded by the Office of Naval Research (grant no. N000140910537) and by the Czech Ministry of Education, Youth and Sports (grant no. LH11051).

References

[1] A. Bowden, K. Hurlburt, E. Aloyo, C. Marts, and A. Lee, "The economic costs of maritime piracy," Oceans Beyond Piracy, One Earth Future Foundation, Tech. Rep., 2011.

[2] Intertanko. (2009, Mar.) Gulf of aden internationally recommended transit corridor & group transit explanation @ONLINE. [Online]. Available: http://www.intertanko.com/upload/IRTC%20%20GT%20Explanation%20-%20March%202009%20(2).pdf

[3] O. Hrstka and O. Vanek, "Optimizing group transit in the gulf of aden," in *15th International Student Conference on Electrical Engineering*, 2011.

[4] M. Chen, D. Kandlur, and P. Yu, "Optimization of the grouped sweeping scheduling (gss) with heterogeneous multimedia streams," in *Proceedings of the first ACM international conference on Multimedia*. ACM, 1993, pp. 235–242.

[5] P. Yu, M. Chen, and D. Kandlur, "Grouped sweeping scheduling for dasd-based multimedia storage management," *Multimedia Systems*, vol. 1, no. 3, pp. 99–109, 1993.

[6] P. Kumar and T. Narendran, "Convoy movement problem–an optimization perspective," *Innovations in Defence Support Systems–1*, pp. 79–93, 2010.

[7] D. Montana, G. Bidwell, G. Vidaver, and J. Herrero, "Scheduling and route selection for military land moves using genetic algorithms," in *Evolutionary Computation, 1999. CEC 99. Proceedings of the 1999 Congress on*, vol. 2. IEEE, 1999.

[8] Maritime Security Centre Horn of Africa (MSCHOA). (2010, August) Gulf of Aden Internationally Recommended Transit Corridor and Group Transit explanation. online.

[9] North of England P&I Assotiation. (2011, July) Loss prevention briefing: Piracy – goa and indian ocean. online. Http://www.nepia.com/cache/files/5693-1315482031/LPBriefing-Piracy-GOAandIndianOcean-080911.PDF.