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Escuela Técnica Superior de Náutica
c/ Gamazo nº1, 39004 SANTANDER
Telfno (942) 201362; Fax (942) 201303
e-mail: info.jmr@unican.es
http://www.jmr.unican.es

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A HEURISTIC FOR VESSEL PLANNING IN A REACH STACKER TERMINAL

J. F. Álvarez[1]

ABSTRACT

The vessel plan must comply with the stowage instructions provided by the shipping line, but should also expedite container transport operations in the yard. This paper presents an algorithm to generate the container ship loading plan using the tabu search and multistart techniques. The proposed algorithm considers the impact of container reshuffling, ground travel, and on-board weight distribution to judge the quality of alternative solutions. The computational performance of the algorithm is benchmarked using a MIP formulation of the problem. Experimental results from a Spanish terminal are presented.

Keywords: Vessel planning, terminal operations, optimization.

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INTRODUCTION

Due to the high capital requirements of owning and operating a modern container ship (Stopford, 1997), the high cost of stevedoring services and equipment, severe competition amongst terminals, as well as the high congestion at many major

[1] Universidad Pompeu Fabra, (josefernando.alvarez@upf.edu), Telf. 618 412 213, Ramón Trias Fargas, Barcelona, Spain.

ports (White and Earnest, 2005), terminal operations must be carried out with the utmost efficiency. One of the most important duties of the terminal staff is directing the timely loading of outbound containers on to the ship, an activity known as vessel planning. Although most modern terminals employ information systems to assist the ship planners in the generation of the vessel plan, many of the tasks involved are still performed manually.

The existing literature provides several exact and approximate algorithms that permit greater automation of vessel planning (see Vis and de Koster, 2003; Steenken, Voβ, and Stahlbock, 2004 for comprehensive literature review on container terminal operations and optimization). However, existing work has focused on terminals that utilize either straddle carriers, rubber-tyred gantry cranes (RTGs), or rail mounted gantry cranes (RMGs). This paper focuses on vessel planning at terminals that operate based on reach-stackers.

In yards that utilize straddle carriers, containers are stacked in single rows, three or four levels high. Adjacent rows are separated by corridors where the straddle carriers travel. One drawback of this layout is that the travel paths take up a significant portion of the yard's floor space. On the other hand, an important advantage of this layout is that any outbound container in the yard can be reached after removing at most three containers.

Due to space limitations, some maritime terminals are laid out in a manner that permits a more intensive use of the yard surface. In these terminals, containers are stored in dense blocks, up to five levels high, and several dozen containers wide by six to twelve containers deep. Straddle carriers can't operate in such yards, as appropriate travel paths are lacking. Consequently, reach-stackers, RTGs, or RMGs are used instead. A drawback of the deep blocks is that access to a given container may be blocked by other boxes. Therefore, it may be necessary to remove and then restack the containers that block access to the target container – an activity known as rehandling, or reshuffling.

RTGs and RMGs remove containers from above, so the potential number of rehandles is limited. Reach-stackers, on the other hand, access containers from the sides of the block, it may thus be necessary to rehandle several dozen containers to reach the target container.

Container rehandling is costly to the terminal, as it reduces operational efficiency and results in extended ship berthing times (a key performance indicator used by shippers to select their preferred terminals). Clearly then, it is essential to sequence the loading of outbound containers to reduce the number of rehandles.

Unfortunately, creating the loading plan by hand is tedious and extremely time consuming. A great number of requirements must be taken into account, such as the container position in the yard, compliance with the shipping line's stowage requirements, allocation of work to several stevedoring teams, obstacles in the yard, and interference between multiple reach-stackers working simultaneously, to name a few.

The central contribution of this paper is an efficient algorithm for vessel planning in container terminals that operate with reach-stackers. In the sections that follow, the paper provides a detailed description of the vessel planning problem. Then, the proposed algorithm is described along with a mixed integer formulation of the problem at hand. Results from several benchmarking and testing exercises are presented, followed by conclusions and directions for future work.

THE VESSEL PLANNING PROBLEM

The yard of a maritime container terminal is organized using four hierarchical levels: blocks, sections, streets, and tiers. A block has a large rectangular footprint, and is organized into sections (perpendicular to the longer axis of the block), and streets (parallel to the main axis of the block). In yards operated with reach-stackers, containers are piled up to five tiers high.

Each block in the yard is designated as either an import or export block. Import blocks accommodate containers that have arrived at the terminal and are awaiting pickup by a truck or train. Because the time at which each container will be picked up is unknown, import containers are sometimes distributed randomly amongst the import blocks. On the other hand, export containers are grouped together by liner company and destination, as this facilitates the removal of a large number of similar containers within a short period of time.

Prior to the arrival of the ship, the ship's operator transmits a stowage plan to the terminal staff. The stowage plan lists the containers that are to be removed from the ship, as well as those that are to be loaded (exports). The stowage plan indicates the ship slots that are to be occupied by the export containers, and the *class* of containers each slot can acommodate. The type, destination, IMO category, and weight category together constitute the container class. Commonly used container types are: DC (standard height dry cargo), HC (high cube), OT (open top), RF (refrigerated), HR (refrigerated high cube), and TA (tank), amongst others. Destination ports are generally specified using six letter abbreviations: three for the country and three for the port. IMO codes designate categories of hazardous cargo, such as flammable liquids or toxic chemicals. A weight category may be given as either light, medium or heavy. Some shippers only specify if the container is loaded or full. For instance, a slot in the stowage plan may be marked GRCPIR-HC20-H-3, to indicate that heavy twenty-foot high-cube container, with materials in IMO category 3, and destination Pireas is to be loaded there. The yard will likely have several export containers in that class. Therefore, the terminal's staff must decide which specific container will be loaded in each slot, as well as the sequence in which the containers will be loaded.

The planning process will typically consist of the following steps. First, the staff must decide how many stevedoring teams will work on the ship in question.

The labor laws and agreements relating to stevedoring practice are complex and vary between localities. The staff at each terminal must be aware of such regulations, as they generally stipulate the number of hours that a crew can work in a shift; the number of workers in each crew; when a crew can be assigned to work sequentially on multiple ships; compensation to the stevedores (including charges for idling, per TEU moved, and surcharges for night or holiday shifts); the composition of each crew (typically a crane operator, a reach-stacker operator, one or two truck drivers, a team coordinator, and one or more latchers on board the ship). The number of teams assigned to the ship also depends on the size of the ship, the number of containers to load, and the level of activity at the terminal.

Once a decision has been made on the number of teams to employ, the ship's holds must be allocated amongst the teams (a task known as the crane split, since each crew is typically assigned to a single quay crane). If all teams are expected to work for the entire shift on the particular vessel, the plan should balance the work load amongst the teams. Alternatively, the staff may attempt to limit the work of one team, in hopes of later reassigning it to a different ship.

After the holds have been assigned to the teams, the planner decides the direction of loading, which can be fore to aft, or vice versa. The planner must ensure that all quay cranes are able to operate simultaneously without interfering with each other.

The quay cranes can load the containers onto the ship using one of several regular patterns (Steenken et al. 2001). As a general rule, and to ensure adequate visibility to the crane operator, containers in a bay are loaded from the sea side towards the land side. The containers can be loaded in vertical columns, or in horizontal layers. In either case, once the loading pattern has been chosen, the order in which the slots of a given hold are loaded is mostly fixed (the planner will ocassionally allow small deviations from the chosen pattern). For the remainder of this paper, it is assumed that the stowage plan and the loading pattern employed by each crane uniquely determine a sequence of generic containers to be loaded on to the ship. The role of the planner from this point on is to assign a specific container to each generic slot, which in turn determines the order in which the containers are to be retrieved from the yard.

In sequencing the loading of containers, the planner attempts to minimize four competing factors:

- Rehandling of containers. When the reach-stacker operator is asked to access a container that is covered by others, he must first remove all the containers that are impeding access to the target container. After removing the target container and loading it on to the truck that delivers it quayside, the reach-stacker operator must, in most cases, restack the containers that were initially removed. This task is complicated because the reach-stacker has limited room to maneuver in the aisles between blocks. Storing containers in the aisles, even temporarily, may not be practical.

- Reach-stacker displacements. Movement of the reach-stacker around the yard must be minimized, as this equipment travels at relatively low speed, and is subject to significant wear and tear.
- Interference between reach-stackers. Multiple reach-stackers have difficulty operating in the vicinity of each other, again due to the limited space in the aisles that separate yard blocks. In addition to the movement of the reach-stacker itself, one must also consider the traffic generated by the fleet of trucks supporting each reach-stacker.
- Ship stability. Finally, the planner must also be mindful of the correct distribution of weight on board, which affects the ship's stability. Although there is no theoretical objection to a heavier container over-stowing a lighter one (British Marine, 2006), the planner generally strives to place heavier containers at the bottom of the holds.

The planner must also specify the "attack side" at each step in the operation. In most cases, a container can be reached from either of the two aisles adjacent to the block. Starting from one such side may result in a lower number of rehandles for the current step and may reposition the reach-stacker favorably for subsequent operations.

Presently, the ship planning process is done by hand at many terminals. This usually entails working on printed copies of the preliminary stowage plan and a list of available containers obtained from a central database. Groups of containers are highlighted in different colors to indicate their load sequence. Generating the plan for a ship loading 500 containers may take between six and eight hours. There is no uniformly accepted method to judge the goodness of a given load plan, and the measures of disutility involved are weighted differently by different planners.

METHODOLOGY

Techniques from Operations Research (OR) have successfully addressed large, complex planning problems in the telecommunications, airline, defense, and manufacturing industries. The impact of OR in the maritime sector has been more modest (Magirou,1992), and many senior managers in the sector remain unaware of this discipline's potential for reducing costs and increasing productivity. The heuristic methods described in the OR literature are particularly well suited to the problems that arise in logistics and maritime operations. This follows from the highly combinatorial nature of these problems and the difficulty of expressing and solving these problems using traditional mathematical programming methods. Heuristic methods in OR differ from exact mathematical formulations in that the former are not guaranteed to reach an optimal solution, although they generally produce remarkably good solutions very quickly (Glover and Kochenberger, 1997).

The algorithm proposed in this paper is based on the tabu search methodology, a technique that has become popular due to its success in quickly obtaining good solutions to complex problems (Glover and Laguna, 1997). Tabu search starts by generating an initial load plan, which although feasible, is readily improved upon. Then, the algorithm iteratively explores alternatives to the current solution by generating "neighboring" plans. These are similar to the current plan, except for relatively minor alterations that are expected to improve the objective value. The algorithm selects the best neighbor, which then becomes the current solution, and begins to explore the neighborhood of this new solution. Cycles are prevented by disallowing the algorithm from undoing its most recent moves, which are considered "tabu".

It is important to note that the quality of the solutions does not improve monotonically – the search can move out of local optima even if this requires a temporary deterioration of the objective value. This allows a broader exploration of plan alternatives. In any event, the "best-yet" solution is always stored. If the search wanders into less desirable alternatives, the algorithm can always return to the best-yet plan. The algorithm terminates after a preset number of iterations, or when no admissible neighbors can be found. The algorithm outputs the best plan it ever created.

The proposed algorithm uses a technique known as multistart. Instead of exploring a single initial plan, a variety of initial plans are generated and explored. This permits a more thorough investigation of the solution space.

Before the tabu search begins, a fair amount of work needs to be done to load the problem data, verify its consistency, and cast it into a format that is amenable to the search procedure. The process starts with the acquisition of all the relevant data for the problem instance, which consist of:

- Spatial layout of the container yard. Name and location of all blocks. Location of aisles and obstacles.
- List of containers currently in the yard. Provides container ID, type (DC, HC, RF, TA, etc.), length, destination, weight, and empty/full designation.
- Geometry of the ship and its bays. Nomenclature for all its slots. Docking position at the quay (starboard or port).
- General stowage plan, specifying a destination, container type, length, and IMO code for each slot to be loaded.
- Number of stevedoring crews available to load the vessel.

The algorithm checks the feasibility of the problem by ensuring that there are enough containers in the yard for each of the different types required in the stowage instructions. Next, the ship's bays are allocated amongst the available stevedoring crews, and a direction of loading for the entire ship is determined (fore to aft, or vice versa). The slots of each group of holds allocated to a stevedoring crew are sequenced according to the order in which they will be filled. Since each position in the sequence can be associated with a slot in the ship, at this point the algorithm has generated one ordered list of generic containers for each crew, as illustrated in Figure 1.

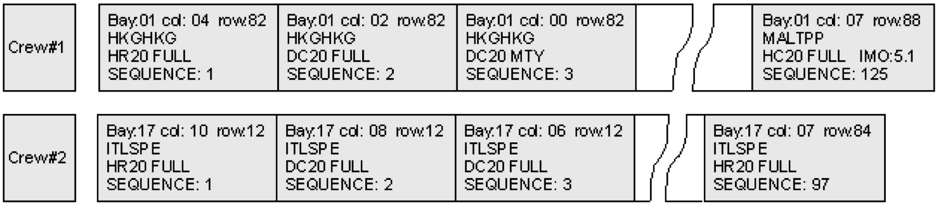

Figure 1: Generic sequences of containers for two crews.

Following Kim et al. (2004), the algorithm establishes which sections of the yard could provide containers of the needed types, and generates a feasible "tour" of the yard. The tour specifies the order in which the yard sections will be visited, and the number of containers that will be collected from each section. Each initial solution uses a different tour orientation, for instance accessing blocks from East to West.

The algorithm then generates an initial plan by assigning a container from the section indicated in the tour to each generic slot. Initial plans thus typically contain sequences of adjacent containers being loaded into adjacent positions in the ship. This method turns out to generate initial plans of good quality.

The cost of the initial plan is calculated as it is being generated. The cost of a plan is computed as the weighted sum of four components: travel of the reach-stacker on the ground, number of containers rehandled in the stacks, disutility due to interference between multiple crews, and a measure of the vertical weight distribution on the ship. The algorithm keeps track of the containers that have been loaded on the ship at any given point, thus providing an accurate count of the number of removal and restacking operations needed to retrieve any given container. Interference between crews is accrued whenever two reach-stackers are scheduled to work within a certain distance of each other. As a proxy to ship stability, the algorithm multiplies the weight of each container by the tier number of the slot it occupies in the vessel. This encourages plans where the lighter containers are placed in the higher slots.

Each iteration of the search begins with the generation of a list of "neighbors" of the current plan. These neighbors are generated from the current plan by exchanging two sequences of equivalent containers, as shown in Figure 2. Noting the multiple ways in which these permutations could be generated, it becomes clear that the number of neighbors could be extremely large. Furthermore, evaluating the cost improvement of each neighbor is computationally expensive, because one must recalculate the new state of the stacks and its impact on reshuffles.

In the interest of computational efficiency, the neighborhood is generated in two steps. The first step considers a large number of neighbors, but computes only a rough (and computationally trivial) approximation of the cost savings of each neighbor. The neighbors are ranked according to this cost proxy, and only the subset at the top of the ranking is retained. A more thorough calculation of the cost benefits of the selected neighbors is then performed, and the best candidate is chosen.

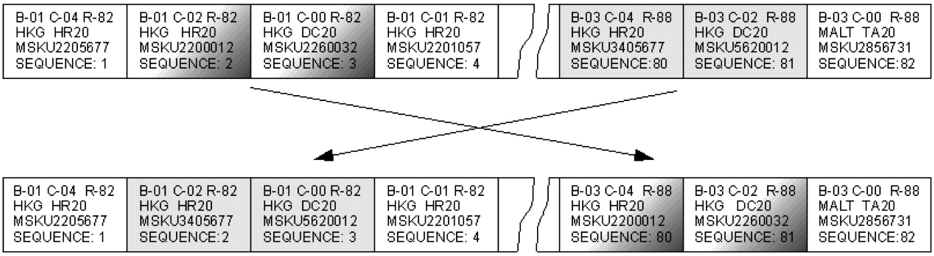

Figure 2: Modifying a plan to generate neighbors.

In forming the first list of neighbors, the algorithm avoids breaking up “least cost” blocks, which are blocks of containers that can be removed from the stack without any unnecessary reshuffling and without any displacement by the reach-stacker. Clearly, these segments can’t be improved upon, and any disruption of their continuity would increase the overall cost of the plan.

The ship load planning problem can also be formulated as a mixed integer program (MIP). The MIP formulation is used to provide a benchmark against which the speed and solution quality of the proposed heuristic can be compared. The formulation uses the binary variables E_p to dictate the attack side (sea- or land-side) at each step p. The binary variables $A_{g,p}$ encode the transition of attack sides on successive steps:

$A_{1,p} = 1$ stands for a sea attacks at $p-1$ and p
$A_{2,p} = 1$ stands for a sea attack at $p-1$ followed by a land attack at p
$A_{3,p} = 1$ stands for a land attack at $p-1$ followed by a sea attack at p
$A_{4,p} = 1$ stands for a land attacks at $p-1$ and p

The MIP presented below addresses a simplified version of the ship planning problem, where only one stevedoring team is assigned to the ship. Therefore, in this formulation the interference between multiple crews is not considered.

Sets

Ξ set of all containers to be loaded
Π set of all vessel slots to be filled. Slots are numbered according to the order in which they must be filled
Υ set of all vessel slots to be filled, excepting the first slot
Γ set of possible transitions in reach-stacker attack orientation: sea-sea, sea-land, land-sea, land-land

Parameters

w_i weight of container i
C_i class of container i
$d_{i,j,g}$ ground distance between yard positions of container i and j when tranj sitioning type is g
$I_{k,i,j,g}$ binary: container k initially blocks access to container j when reach stacker starts from container i and transitioning type is g
$B_{i,j,g}$ number of containers initially required to remove container i when starting from the position of container j and transitioning type is g
$V_{i,g}$ number of containers required to access container i when it is the first container in the sequence, and transitioning type is g
S_p class of containers accepted by slot p in vessel
l_p arm of ship slot p for stability purposes
α_s objective function coefficient for container rehandling
α_d objective function coefficient for distance travelled on the ground
α_w objective function coefficient for vertical instability
M suitably large number

Variables

$X_{i,p}$ binary, container i loads at step p in load sequence
E_p binary, attack side (sea=0, land=1) at step p in load sequence
$A_{g,p}$ binary, attack transition is g at load step p
R_p integer, total number of boxes cleared at step p in load sequence
D_p ground distance traveled during loading step p
W_p instability disutility of container placed in slot p

Minimize

$$z_{MIP} = \alpha_s \sum_{p\in\Pi} R_p + \alpha_d \sum_{p\in\Pi} D_p + \alpha_w \sum_{p\in\Pi} W_p \quad (1)$$

Subject to:

$$\sum_{i\in\Xi} X_{i,p} = 1 \quad \forall p \in \Pi \quad (2a)$$

$$\sum_{p\in\Pi} X_{i,p} = 1 \quad \forall i \in \Xi \quad (2b)$$

$$S_p \geq C_i - M(1 - X_{i,p}) \quad \forall p \in \Pi, \forall i \in \Xi \tag{3a}$$

$$C_i \geq S_p - M(1 - X_{i,p}) \quad \forall p \in \Pi, \forall i \in \Xi \tag{3b}$$

$$R_p \geq B_{i,j,g} - \sum_{s=1}^{p-1} \sum_{k \in \Xi} X_{k,s} I_{k,i,j,g} - M(1 - A_{g,p}) - M(2 - X_{i,p-1} - X_{j,p})$$
$$\forall p \in \Upsilon, \forall i \in \Xi, \forall j \in \Xi, \forall g \in \Gamma \tag{4}$$

$$R_1 \geq \sum_i V_{i,g} X_{i,1} - M(1 - A_{g,1}) \quad \forall g \in \Gamma \tag{5}$$

$$\sum_{g \in \Gamma} A_{g,p} = 1 \quad \forall p \in \Pi \tag{6}$$

$$4A_{4,p} + 3A_{3,p} + 2A_{2,p} + A_{1,p} = 2E_{p-1} + E_p + 1 \quad \forall p \in \Pi \tag{7}$$

$$D_p \geq d_{i,j,g} - M(1 - A_{g,p}) - M(1 - X_{i,p-1}) - M(1 - X_{j,p})$$
$$\forall p \in \Upsilon, \forall i \in \Xi, \forall j \in \Xi, \forall g \in \Gamma \tag{8}$$

$$W_p = \sum_{i \in \Xi} l_p w_i X_{i,p} \quad \forall p \in \Pi \tag{9}$$

$$X_{i,p}, Y_{i,j}, E_p, A_{g,p} \in \{0,1\} \tag{10a}$$

$$R_p \geq 0, integer \tag{10b}$$

$$D_p, W_p \geq 0 \tag{10c}$$

Constraints (2a) and (2b) require that each container be assigned to exactly one vessel slot. Constraints (3a) and (3b) ensure the class of container assigned to each slot corresponds to that slot's class designation in the stowage plan. Constraint (4) computes the number of rehandles at step p. The constraint starts with $B_{i,j,g}$, the number of rehandles required to reach the container being loaded in step p when no containers have been removed from the yard. The double summation serves to adjust that initial rehandle count downward, according to the number of containers that have been already loaded, and that were previously an obstacle to reaching j, the target container. Constraint (5) computes the number of shifts at the first step in the loading sequence, a specialized version of constraint (4). Constraints (6) and (7) define the transition types $A_{g,p}$ in terms of the attack position of the reach-stacker at steps p and p-1. Constraint (8) computes the total ground distance traveled during step p. Constraint (9) computes the vertical instability disutility due to the container in slot p. Constraints (10a), (10b), and (10c) address the integrality and non-negativity of the decision variables.

Experimental Results and Analysis

The algorithm was tested throughout the implementation process using actual data from ten ships loading a small number of containers (30-100 TEUs) at a Spanish port. This guided the development effort by shedding light on the benefits and computational requirements of different variants of the algorithm. Experienced ship planners reviewed the results and offered their guidance in this respect.

Having finalized the fundamental design of the algorithm, a second set of experimental runs was performed. This set of tests fulfilled three objectives. First, it permitted a formal assessment of the benefits of the multistart technique. Second, it allowed for an understanding of the trajectory of the objective function as the algorithm progresses. Finally, the tests illustrated the impact of the neighborhood size on the solution quality.

The data for these tests were based on three ships of 2,000, 4,500, and 7,000 TEU, and loading 74, 407, and 591 containers, respectively. Additional cases were generated by bootstrapping the three base cases (by exchanging the location of no more than 10% of the ship's containers). The tests were run using five multistart plans. These tests were done on an 800 MHz Pentium III computer.

All runs were completed in one to five minutes. Initial solutions of good quality were generated in less than five seconds. The results indicate that the initial plans may be quite dissimilar, with objective values differing by up to 15%. The search algorithm can improve an initial plan by up to 35%, but occasionally the improvement is as low as 1%. The best initial plan does not always lead to the best final plan, and the search process can transform similar initial plans into very dissimilar final plans. These observations indicate that multistart is indeed valuable. For larger ships, the quality of the solution would likely benefit from a larger number of initial plans.

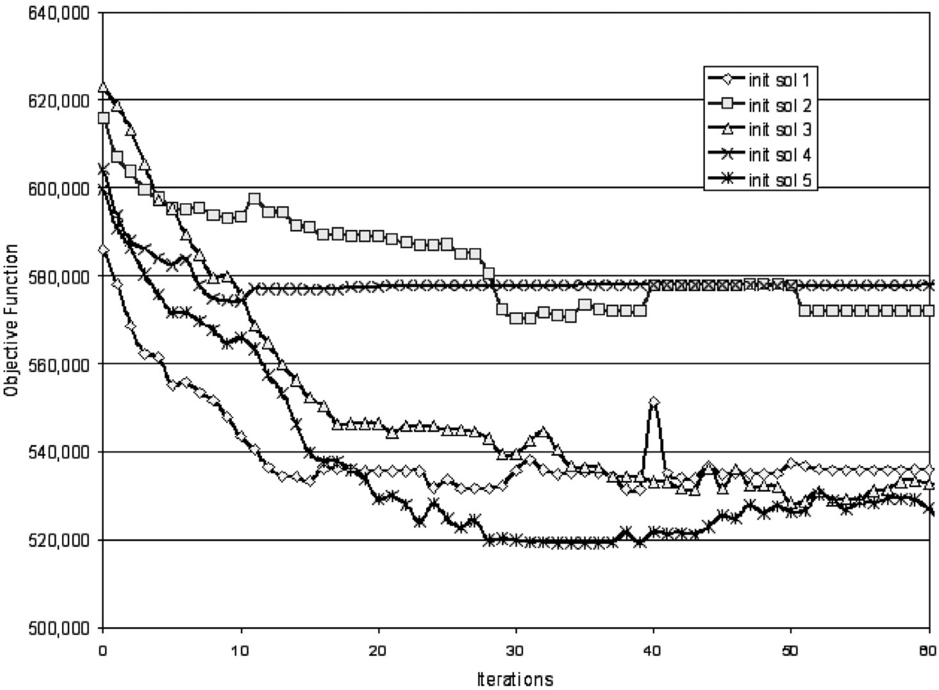

Figure 3: Objective function trajectory for 4,500 TEU ship.

As is often observed with tabu search, in these experiments the objective function improves rapidly during the initial iterations, and then oscillates within a relatively narrow range. After a small number of iterations (about 15 for the small ship and 40 for the larger ships), the algorithm has achieved most of the improvements it would likely ever achieve (as verified by running the algorithm for a very large number of iterations). This is illustrated in Figure 3. It is thus plausible to run the algorithm until either convergence is achieved, or for a problem-specific number of iterations. The speed of convergence will depend on the size of the neighborhoods. For this problem, generating large neighborhoods is computationally expensive, and it is therefore preferable to perform a larger number of iterations on smaller neighborhoods.

As mentioned previosuly, the algorithm chooses the best neighbor using a two-phase selection process. Since the cost proxy used in the first phase is an approximation, many low-quality neighbors are initially ranked incorrectly as cost-improving options. If too many neighbors are generated, these ”false positives” displace the truly cost-improving neighbors from the ranking, and choke the selection process. It is therefore important to provide sufficient space in the ranking vector to allow for this effect. Other techniques, such as stochastic selection of neighbors are promising in this regard.

In a third set of experiments, the MIP formulation presented above was implemented using AMPL 9 (Fourer et al 2003), and solved using CPLEX 9.0 (ILOG 2005). These experiments were run on a 1600 MHz Pentium M computer with 512 MB of RAM. No instance with more than 40 containers was successfully solved. In these cases, the presolve phase consumed all the RAM in the test machine, with which the runs were cancelled.

Two small examples with 22 and 29 containers were successfully solved. In these cases, the MIP solutions obtained after three minutes were 20%-30% worse than the initial solutions obtained by the proposed heuristic.

CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

This paper presented an application of tabu search and multistart to the automation of the vessel planning process in maritime terminals. The proposed algorithm is specifically tailored to terminals that operate their yards with reach stackers. The algorithm has been informally praised by experienced ship planners based on the results obtained for a set of real-world tests. The algorithm finds good solutions very quickly, and can solve problems with hundreds of containers in a few minutes.

There exist numerous directions for further research. First, further comparison of the plans produced by the algorithm against those produced manually is desirable. A more tractable definition of what constitutes acceptable tradeoffs between the multiple measures being minimized in the planning process must be sought and coded into the algorithm. In this regard, it may be possible to extend the algorithm to a true multi-objective search. This approach would allow the decision makers to better understand the qualities of the different planning options, and guide the algorithm towards the preferred solution space.

The findings in this research indicate that standard MIP formulations are inadequate for solving actual instances of the ship load planning problem. The basic MIP formulation is unable to address problems with as little as 40 containers. In order to perform a plausible calibration of the metaheuristic against established MIP solution software, more sophisticated modelling techniques will be necessary. In this the combination of traditional mathematical programming methods with metaheuristics is a promising direction of research.

The speed of the algorithm is satisfactory, largely due to the use of cost proxies in neighborhood generation. Further enhancements to the accuracy of the cost proxy are possible. Regression testing of different proxy formulae would be a straightforward manner of reaching this goal.

Some of the ideas presented in this paper are applicable to terminals operating with different types of stacking equipment. Most terminals in the Far East operate mixed fleets of stacking equipment, but emphasize rubber-tired gantry cranes (M. Lambert et al., 2005). There is currently a manifest demand for algorithms to optimize the utilization of the latter.

REFERENCES

Alderton, P. (2005): Reeds Sea Transport Operations and Economics. Thomas Reed Publications, 5th edition.

Ebru K. Bish, Frank Y. Chen, Yin Thin Leong, Barry L. Nelson, Jonathan Wing, Cheong Ng, and David Simchi-Levi (2005): Dispatching vehicles in a mega container terminal. *OR Spectrum,* 27, 491-506.

Fourer, R., Gay, D. and Kernighan, B.W. (2003): AMPL, A Modeling Language for Mathematical Programming. Duxbury, Toronto, 2nd edition.

Glover, F. and M. Laguna, M. (1997): Tabu Search. Kluwer Academic, Boston.

Glover, F. and Kochenberger, G., editors (2003): Handbook of Metaheuristics. Kluwer Academic, Boston,.

ILOG, S.A. (2005): ILOG CPLEX Reference Manual. Mountainview, California.

Kim K.H., Kang J.S., and Ryu K.R. (2004): A beam search algorithm for the load sequencing of outbound containers in port container terminals. *OR Spectrum* 26

Lambert, M. (2005): Containerization International Yearbook. Emap Business Communications, Ltd, London.

Magirou, E.F. , Psaraftis, H.N. and Christodoulakis N.M. (1992): Quantitative methods in shipping : A survey of current use and future trends. Technical Report E115, Center for Economic Research, Athens University of Economics and Business, Athens.

Stopford, M. (1997): Maritime Economics. Routledge, New York, 2nd edition.

Steenken, D., Voß S., andStahlbock, R. (2004): Container terminal operation and operations research – a classification and literature review. *OR Spectrum,* 26.

British Marine (2006): Container Securing [online]. Available from: http://www.britishmarine.com/tech/bm106.htm. [Accessed December 21 2006]

Vis, I.F.A. and de Koster, R. (2003): Transhipment of containers at a container terminal: An overview. *European Journal of Operations Research,* 147.

White, R. D. and Earnest, L. (Jan 23 2005): Congestion at cargo ports worldwide. *The Los Angeles Times.*

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THE ICARUS PORTAL: AN AID TO IMPROVE SAFETY OF NAVIGATION

F. X. Martínez de Osés[1] and S. Velásquez Correa[2]

ABSTRACT

Leisure ships and non SOLAS (International Convention for Safety of Life At Sea) ships as fishing vessels or small tugs, are not subjected to International Maritime Organization (IMO) standards related to the equipment, but by the classification societies through additional requirements related to the control centre physical distribution.

The ICARUS concept tries to provide to the end users, a practical tool supplying information from the books collection on board like Pilot books and others as well as meteorological information and weather forecasting, all integrated in an internet portal, accessible from portable devices like the latest generation mobile phones or palms. GPS or positioning systems will make possible to update information and selected screens will display data required by means of a complete menu. Today communication and internet based technologies with the support of GIS technologies have created a very friendly environment. XML and JAVA technologies have been used for the data interchange and software development in the end user's application.

Keywords: Safety data, non SOLAS crafts, GIS, XML, JAVA, portable receivers.

INTRODUCTION

Among the most important data required by seafarers is that related to the weather; meteorological observation from ships has been a major pillar supporting

[1] Profesor lector y Secretario del Departamento de Ciencia e Ingeniería Náuticas de la Universidad Politécnica de Cataluña (fmartinez@cen.upc.edu), Pla Palau, 18, 08003 Barcelona, Spain. [2] Investigador del Centro de Estudios Técnico Marítimos, SL (CETEMAR) (sergio@cetemar.com), Carrer l'Escar 6-8, 08039, Barcelona, Spain.

this modern science. In the sea side, the automation on board merchant ships suffered during some decades, a kind of blocking that has changed only some years ago towards a progressive assimilation of the technical advances offered in the market. Thus affording the ship's technical, functional and operational integration.

Within the control centres on board, referred as not only the ship's navigation bridge but also the functions carried out in it by their users and the technology used, from the mid nineties, it has been possible to percept (verify) the number of integrated bridges is growing, even though they are fitting integrated navigation systems. However non SOLAS ships as fishing vessels or sailing crafts are not subjected to IMO standards related to the equipment and other information systems requirements. But sometimes those standards could be a guide to be followed while the manufacturing cost is maintained in low levels.

THE QUESTION IN ITSELF

The basic requirement when a ship is going to proceed to any port is not always safety but cost and time minimization, when calculating the track. Talking about costs, we can consider fuel consumption, time or even risks. In land navigation, the vehicle is restricted to the existing ways or roads and very little modifications are possible. But in the sea navigation the different chances widen due to the freedom to select any track for going from one port to another except when the weather conditions deteriorate as existing tropical revolving storms or any other heavy weather conditions.(Martínez de Osés, 2003)

The optimal track calculation and side information from pilot books and guides (sailing directions) are important parameters to be considered in the present paper.

The optimal track calculation

On a spherical surface the shorter way is the great circle track. For this purpose the sailor uses the spherical trigonometric and the great circle formulae, obtaining the first course through: $R = (\text{tg } l_B \cos l_A - \sin l_A \cos \Delta L) / \sin \Delta L$

and the distance: $D = \sin l_A \sin l_B + \cos l_A \cos l_B \cos \Delta L$

(being l the latitude and L the longitude).

Obviously the time will be obtained dividing the distance by the mean speed. However the resulting arc used to be converted into a polygonal track, using a series of *waypoints*, as the ship is going to follow a series of short but different tracks, describing an arc.

From those mathematical solutions we can calculate an optimum track for minimising the fuel consumption. And the only limitation (apart from islands and dangers to navigation) is to sail on higher latitudes, where weather deteriorates fast. But is it possible to approximate the most efficient track considering the avoidance of the worst weather?. We know that this is not always true because the longer is the voyage the more incidences of external forces can be received, as wind, waves and currents. At that time we are going to need to refresh the calculations redrawing the track.

The question is: "can a computer do those calculations?". We are convinced that the everyday improvement suffered by the software and computers, points to the affirmative answer. The question is to know how to programme the software and how to provide it with the proper data (Nilsson, 2001).

THE GRAPHICS

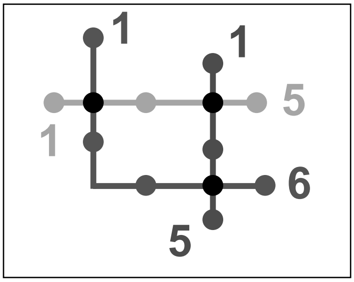


Fig. 1. Metropolitan map

The graphics is a mathematical resource used for computing purposes.

We can define it as a set of elements called vortex together with another group of those vortex pairs, called sides. Both can be represented by means of points connected by straight lines. One can see an everyday example in a metropolitan map.

If we can go from the blue –green link to the blue– red one, what is the best route?. In a first step we are going to need the times, those can be represented by means of a matrix.

Up side way 1+2+1+2 = 6 minutes.

Down side way 2+3+2 = 7 minutes.

So the best option is the up side one.

THE NAVIGATION

	1	AV	3	4	AR	6	1	3	RV	5	1	3	5
1		1											
AV	1		2				2	1					
3		2		3									
4			3		2								
AR				2		1						2	2
6					1								
1		2											
3		1							2				
RV								2		3	2	1	
5									3				
1									2				
3					2				1				
5					2								

Fig. 2. Time table for reaching the metropolitan nodes

Applying the previous concepts to navigation where no physical connections are, we must create them, using for example, the following options:

a) Fixed net with variable weights

The vortex is geographically fixed and each side has a variable weight depending on

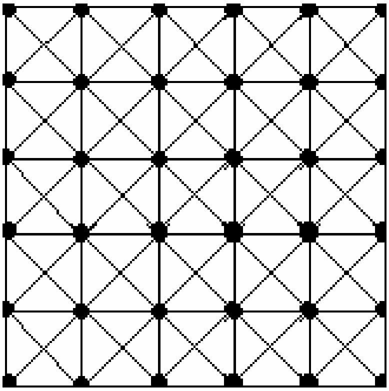


Fig. 3. Example of a net

the weather conditions in the area. So the optimum path will deviate from those areas.

The prohibited areas (land, reefs, etc.) will have no sides or the sides will have an infinitum weight.

b) Variable net

In this case the sides are going to have a constant weight and the vortex will change their geographic position. One example is the isochrones method, proposed originally in 1957 by R. W. James.

From the beginning the navigator will open several different courses at intervals of 5, 10 or 15 degrees. Further the track will be drawn depending on the effective speed developed on a constant time basis. The speed will depend on weather conditions. (Hagiwara , 1989)

The process will be repeated as far as reaching the destination, completing what is called a tree.

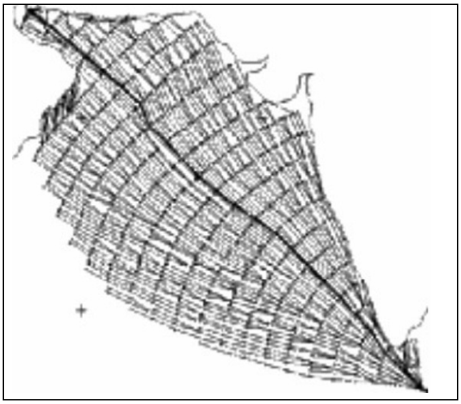


Fig. 4. Track built on an isochrones method.

The only problem is the big volume of data to be managed in order to do efficient optimisations. In that situation the classical algorithms (Floyd, Dijkstra et alt) are not so effective due to the way of working, looking for all the vortex, even those too many away from the destination point. (Bauk, 2003) Then it is needed to apply heuristics technical for reducing the searching room, using for example artificial intelligence as the A star algorithm. (Sanjuán Mourelo and Martínez de Osés, 2005)

GENERAL DESIGN OF THE APPLICATION

One of the main components on the service is "The Electronic Pilot Book", hereafter called the E-Pilot Book, which consists of an integrated information system; this system includes the required information by the end users and has its origin in different text and graphic sources. Pilot book has bee designed by Cetemar, SL in several applications as in EPDIS project 5th Framework Programme. IST directorate co-funded project (EU Commission). This system will store and handle the static data contained in the ICARUS portal, currently available in the paper-based pilot books.

Because this information is distinct in nature, it first needs to be interpreted and then integrated into a system for its handling, access and querying processes. Therefore, data has been grouped into subsets depending on their sources. For this task the database concepts and dynamic information are of fundamental importance.

Source: www.cetemar.com, 2006

Fig. 5. ICARUS Start page with pilot book functions

The information contained in navigational databases, includes geographical coordinates; hydrographical, geographical and charting information; shipping legislation and ruling; references to aids to navigation; waypoints and meteorological data. The navigational databases have a set of specific characteristics that set them apart from the others that provides for more efficient use. At the same time they do have some common features with other databases making possible to relate them with others databases.

Some details are:

1. They must be periodically up-datable in accordance with the control and legal cycles for international shipping information.

Source: www.cetemar.com, 2006.

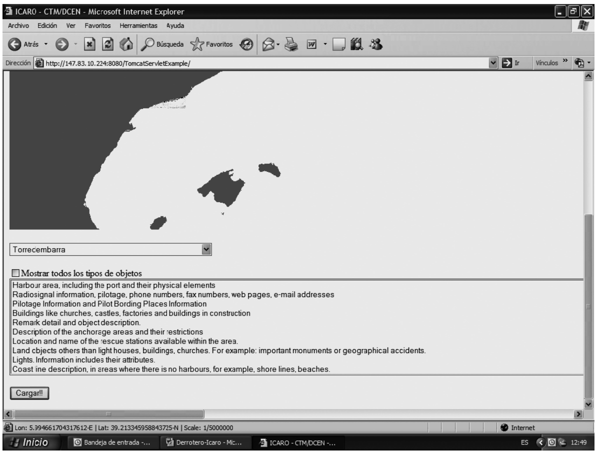


Fig. 6. Pilot book main page showing searching lists.

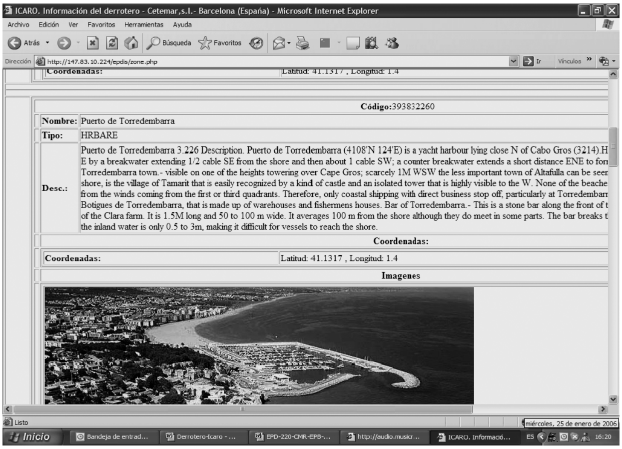
2. The user of ICARUS will have access to official and updated information. For this purpose the database should have a valid period, showing an alert if it has not been possible to update it or when the valid date expires.
3. Integrity and data quality must guarantee precise navigation.
4. The end user will not be able to access or modify the contents of the databases.

COASTAL NAVIGATION AID SYSTEM. SERVICE DESCRIPTION

The ICARUS concept provides a service of maritime navigation aid within a context of portable consoles and limited possibility devices and/or laptops, served by internet; the service is operated in boats of small dimensions (coastal traders) and preferably leisure ships.

The idea is to provide a system framed within the marine navigation aids and which tries to make an expert treatment of the information available and accessible from established criteria, based on safety; after the analysis of operative and security needs from the navigators point of view. This idea proposes a conceptual system for its future implementation under an client-server architecture and supported on portable and ergonomic type devices like agendas or pocket PCs, mobile telephones or laptops. These terminals would have internet connection by means of mobile GPRS communications, either another available wireless connection in the surroundings of navigation, harbour approaches or when the boat is in the port.

The service integrated in a web portal will provide a solution to some problems when the navigators are near to the coastline or when they want to plan a safe and fast route until his port of destination, making possible the access to the official information mainly available for professional mariners and ruled for the IMO boats.



Source: www.cetemar.com, 2006

Fig. 7. Port searching example in the electronic pilot book.

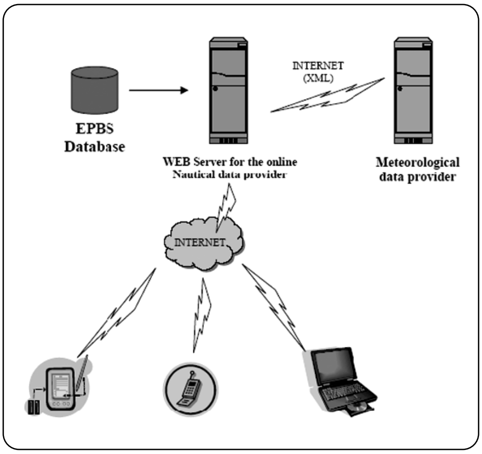
In this way all the limitations of paper guides, known like "map courses", in terms of ergonomics and updating, are avoided. Apart of the innovating of this business idea, the main target is to improve the safety in the leisure navigation, exploiting to the maximum the present information and communication technologies reaches.

ICARUS SYSTEM DESCRIPTION

Part of the information supplied by the service comes from some of the IMO ruled paper books like Pilot and Sailing directions, light and radio-signal and guides to port entry books. This point must be strongly considered because of the copyright rules as official publications are edited and published for the Hydrographical Organizations at local and international level; for example the *Instituto Hidrográfico de la*

Marina de Cádiz, in Spain, or the UKHO *"United Kingdom Hydrographic Office"* Admiralty charts and publications. This part of the service is managed by a large database system; its implementation has taken into account the International Hydrographical Organization (IHO) rules for the implementation of maritime and hydrographical information, using the guides in their standard 57 (S57).

Legal and copyright procedures have been discussed with the hydrographical offices involved, in our case: IHO, UKHO and the *Instituto Hidrográfico de la Marina de Cádiz* have been contacted, thus, official and updated information is supplied. Data is organized implementing a database which considers object oriented programming, the main goal using this concept is the possibility in adding a special attribute to the records on database (Objects): **"the geo-reference"**. Using geo-references, queries and updating processes are easier handling. Interaction with GPS signal is actually possible when geo-references are used.



Source: www.cetemar.com, 2006

Fig. 8. ICARUS system description.

E-PILOT BOOK FUNCTIONS

The E-Pilot Book has been designed to provide an easy way for the user to query and search for the information. The WEB environment supported by HTML design is ideal for this purpose (See http://www.cetemar.com). The user starts out at the index page to initiate the search from a collection of pilot books data listed for a given area. The user can either implement the search option or browse the route marks for the area of interest. This last option provides access to the Pilot Text Page or the Objects, such as land marks, lights, aids to navigation, and so on. The main point for the ICARUS and E-pilot book are the easy linkage of information by means of geo-references which makes possible to view information by means of the position clicking on a specific place on the charts available on the portal. It is important to notice that the end user application does not depend on the operative system platform, memory or hard disk capacity of his device. XML, web services, SQL database management and JAVA technologies improve the ICARUS capabilities. The ICARUS portal includes other possibilities for accessing information related with sea, wave and wind behaviour on real time. A future development will include the optimal route calculation, where meteorological and sea parameters would be considered.

CONCLUSIONS

At this project development stage, it is very soon to point out some solid conclusions. However we can confirm that main problems foreseen in the near future are not coming from the optimum route calculation engine, but from the availability of high quality weather information. It is needed that proper geo-referenced data are ready to be translated into graphic, clear and intelligible safety information for the leisure sailor.

Legislation is almost behind of the industry needs. It means that weather information devices required on board can not cover the data needed for a global weather vision. There are a lot of services to optimise tracks. The only problem is the cost and sometimes the data availability once the ship has passed the weather episodes.

Regarding the algorithms we think that Dijkstra one needs a big calculation capacity, so they are needed heuristic methods that could discard the worst cases, then concentrating the computing resources in the possible paths.

An integrated information system for leisure ships must be friendly user and accessible; the end user not necessary has to think in the internal algorithms involved neither the platforms he must carry for displaying information. The advantage and added value on ICARUS service is the possibility of having access to official information and advanced calculations needed from a field of user not always being professional mariners. Current information technologies make possible to take this step forward in the leisure ships industry.

REFERENCES

International Convention for Safety of Life At Sea. International Maritime Organization Publishing, 2004.

International Maritime Organization.

Martínez de Osés, F.X. *Metodología y criterios para el desarrollo de un sistema integrado de información meteorológica y oceanográfica.* PhD Thesis Barcelona 2003.

Nilsson, N. J. *Inteligencia artificial: una nueva síntesis,* Barcelona 2001 McGraw Hill Ed.

Hagiwara,H. *Weather routing of (sail-assisted) motor vessels,* Technische Univ. PhD Thesis Delft 1989.

Bauk S I. *Solving TSP in navigation by application of hopfield recurrent neural network.* Edited by Olivella, J., García Carcellé, V., García Domingo, E. *Maritime transport II.* Barcelona SCI UPC, 2003.

Sanjuán Mourelo, D., Martínez de Osés, F.X. *Derrota meteorológica: adquisición y procesamiento de datos mediante teoría de grafos.* Degree Master thesis of the first author, Barcelona 2005.

EL PORTAL ICARUS: UN SISTEMA DE AYUDA A LA NAVEGACIÓN

El presente artículo pretende dar a conocer un sistema de ayuda a la navegación para embarcaciones no SOLAS, que esté disponible a través de un portal donde la aplicación va a permitir descargar cartografía de calidad, información para la navegación y en un futuro la optimización de la derrota en función de la información meteorológica.

Las embarcaciones menores en general y las de recreo en concreto no están sujetas a la legislación SOLAS, aunque cabe aclarar que el cumplimiento del capítulo V del mismo está recomendado en todos los casos, aunque las sociedades de clasificación pueden establecer requisitos adicionales. Con ello pretendemos decir que el nivel de seguridad exigible legalmente en este tipo de buques no es el mismo que en los buques SOLAS.

El concepto propuesto en ÍCARO es el de proporcionar a los usuarios una herramienta, que en línea con el tipo de información exigible a todo buque en cuanto a publicaciones náuticas y derroteros, práctica y que proporcione información de las publicaciones que debe de llevar todo buque a bordo así como la posible previsión meteorológica y la recomendación de la derrota mediante un algoritmo de cálculo. Todo ello disponible desde un servidor que bajo demanda transmitiría dicha información a un recetor portátil como un teléfono móvil de última generación o una PDA.

Gracias a la integración de un sistema de posicionamiento GPS, las tecnologías basadas en internet con el soporte de técnicas GIS, permiten crear un entorno de intercambio de información que permite hacer funcionar aplicaciones como la presentada.

Una de las bases de esta aplicación, es el E-pilot book o derrotero electrónico, la cual en diseño HTML, corre en el portal ICARO. El usuario simplemente debe de conectarse al servidor y posteriormente usar la opción de búsqueda o simplemente indagar en las marcas o señales de navegación existentes en el área. La principal utilidad del sistema permite llamar la información sobre un punto, de forma fácil con lo que se descargan no sólo características e los puntos que consultamos, sino también la carta de la zona y el texto que correspondería en el lugar proveniente del derrotero.

Otra baza del sistema, es el hecho de que la aplicación no descansa sobre el sistema operativo del usuario. Adicionalmente pueden descargarse la información sobre oleaje, viento y en un futuro la derrota recomendada en función de esta información.

Como conclusión aparte del desarrollo en si mismo de la aplicación, es la obtención de información de calidad tanto cartográfica como meteorológica. En el primer caso la empresa que desarrolla la aplicación tiene acuerdos tanto con el Servicio Hidrográfico de la Marina y el Almirantazgo Inglés.

La utilidad meteorológica inicialmente apuesta por un auténtico servicio de asesoramiento y no sólo de reporte a, optando por un método de desarrollo heurístico que evitaría tener que calcular todos los nodos como es el caso del algoritmo de Dijkstra.

En cuanto a la ergonomía y facilidad de uso, esta se ve ayudada por el hecho de que un marino con titulación deportiva y poca experiencia profesional, no deberá de preocuparse por cálculos e interpretaciones de la información, que el receptor la proporcionará ya tratada.

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ODD LEVEL SET: A NEW METHOD FOR SIMULATION OF FREE SURFACE PROBLEMS

J. García Espinosa[1], A. Valls Tomas[2]

ABSTRACT

This paper introduces a new stabilized finite element method based on FIC (Oñate and García, 2001; Oñate et al, 2004; García et al, 2005) and ALE techniques (Hirt et al, 1974), specially developed for analysis of naval hydrodynamics problems. The main innovation of this method is the application of domain decomposition concept in the statement of the problem, in order to increase accuracy in the capture of free surface as well as in the resolution of governing equations in the interface between the two fluids. Free surface capturing is based on the solution of a level set equation, while Navier Stokes equations are solved using an iterative monolithic predictor-corrector algorithm (Codina, 2001), where the correction step is based on the imposition of the divergence free condition in the velocity field by means of the solution of a scalar equation for the pressure. In this paper an application of the new methodology to the simulation of roll movement in a real geometry of a high speed craft is presented.

Key words: Finite Element Method (FEM), Free Surface, Naval Hydrodynamics, Navier Stokes, Level Set, Domain Decomposition.

STATEMENT OF THE PROBLEM

The velocity and pressure fields of two incompressible and immiscible fluids moving in the domain $\Omega \subset \boldsymbol{R}^d$ (d=2,3) can be described by the incompressible

[1] Profesor, Aula FNB CIMNE, Facultad de Náutica de Barcelona (UPC) (julio@compassis.com), Pla del Palau, 18, 08003, Barcelona, Spain. [2] Investigador, COMPASS Ingeniería y Sistema S.A. (aleix@compassis.com), C/ Tuset 8, 7º, 2ª, 08004, Barcelona, Spain.

Navier Stokes equations for multiphase flows, also known as non-homogeneus incompressible Navier Stokes equations (Lions, 1996):

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}(\rho u)=0$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)+\frac{\partial p}{\partial x_i}-\frac{\partial \tau_{ij}}{\partial x_j}=\rho f_i \tag{1}$$

$$\frac{\partial u_i}{\partial x_i}=0$$

Where $1 \leq i, \leq j\, d$, ρ is the fluid density field, u_i is the ith component of the velocity field u in the global reference system x_i, p is the pressure field and τ is the viscous stress tensor defined by:

$$\tau_{ij}=\mu\left(\partial_i u_j+\partial_j u_i\right) \tag{2}$$

where μ is the dynamic viscosity.

Let $\Omega_1=\{x\in\Omega | x\in \text{Fluid1}\}$ be the part of the domain Ω occupied by the fluid number 1 and let $\Omega_2=\{x\in\Omega | x\in \text{Fluid2}\}$ be the part of the domain Ω occupied by fluid number 2. Therefore Ω_1, Ω_2 are two disjoint subdomains of Ω. Then

$$\Omega=\operatorname{int}\left(\overline{\Omega_1 \cap \Omega_2}\right) \tag{3}$$

The system of equations (1) must be completed with the necessary initial and boundary conditions, as shown below.

It is usual in the literature to consider that the first equation of the system (1) is equivalent to impose a divergence free velocity field (the third equation in (1)), since the density is taken as a constant. However, in the case of multiphase incompressible flows, density can not be consider constant in $\Omega\times(0,T)$. Actually, it is possible to define ρ,μ fields as follows:

$$\rho,\mu=\begin{cases}\rho_1,\mu_1 & x\in\Omega_1\\ \rho_2,\mu_2 & x\in\Omega_2\end{cases} \tag{4}$$

Let $\psi\colon \Omega\times(0,T)\rightarrow\mathbb{R}$ be a function, in below named Level Set function, defined as follows:

$$\psi(x,t)=\begin{cases} d(x,t) & x\in\Omega_1 \\ 0 & x\in\Gamma \\ -d(x,t) & x\in\Omega_2 \end{cases} \tag{5}$$

where $d(x,t)$ is the distance to the interface between the two fluids, denoted by Γ, of the point x in the time instant t. From definition (5) it is trivially obtained that:

$$\Gamma=\{x\in\Omega \,|\, \psi(x,\cdot)=0\} \tag{6}$$

Since the level set 0 identify the free surface between the two fluids, the following relations can be obtained:

$$n(x,t)=\nabla\psi\big|_{(x,t)} \;;\; \kappa(x,t)=\nabla\cdot\big(n(x,t)\big) \tag{7}$$

where n is the normal vector to the interface Γ, oriented from fluid 1 to fluid 2 and κ is the curvature of the free surface. In order to obtain relations (7) it has been assumed that function ψ defined in (5) accomplish (Osher and Sethian, 1988; Osher and Fedkiw, 2001; Fedkiw et al, 1999):

$$\|\nabla\psi\|=1 \qquad \forall(x,t)\in\Omega\times(0,T) \tag{8}$$

Therefore, it is possible to re-write definition (4) as follows:

$$\rho,\mu=\begin{cases} \rho_1,\mu_1 & \psi>0 \\ \rho_2,\mu_2 & \psi<0 \end{cases} \tag{9}$$

Let us write the density fields in terms of the level set function ψ as

$$\rho(x,t)=\rho\big(\psi(x,t)\big) \quad \forall(x,t)\in\Omega\times(0,T) \tag{10}$$

Then, density derivatives can be written as

$$\frac{\partial\rho}{\partial t}=\frac{\partial\rho}{\partial\psi}\frac{\partial\psi}{\partial t}, \quad \frac{\partial\rho}{\partial x_i}=\frac{\partial\rho}{\partial\psi}\frac{\partial\psi}{\partial x_i} \tag{11}$$

Inserting relation (11) in the first equation of the system (1) gives

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)\underset{\frac{\partial u_i}{\partial x_i}=0}{=}\frac{\partial \rho}{\partial t}+u_i\frac{\partial \rho}{\partial x_i}=\frac{\partial \rho}{\partial \psi}\frac{\partial \psi}{\partial t}+\frac{\partial \rho}{\partial \psi}u_i\frac{\partial \psi}{\partial x_i}=\frac{\partial \rho}{\partial \psi}\left[\frac{\partial \psi}{\partial t}+u_i\frac{\partial \psi}{\partial x_i}\right]=0 \quad (12)$$

What gives as a result that the multiphase Navier Stokes problem (1) are equivalent to solve the following system of equations:

$$\begin{aligned}\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)+\frac{\partial p}{\partial x_i}-\frac{\partial \tau_{ij}}{\partial x_j}&=\rho f_i\\ \frac{\partial u_i}{\partial x_i}&=0\end{aligned} \quad (13)$$

coupled with the equation

$$\frac{\partial \psi}{\partial t}+u_i\frac{\partial \psi}{\partial x_i}=0 \quad (14)$$

Equation (14) defines the transport of the level set function due to the velocity field obtained by solving (13).

As a conclusion, the free surface capturing problem can be described by equations (13) and (14). In this formulation, the interface between the two fluids is defined by the level set 0 of ψ.

It is possible to demonstrate, assuming the variables of the problem as sufficiently smooth, that the system (1) or equivalently the system given by equations (13) and (14) has a unique global solution (Lions, 1996).

Denoting by over-bar the prescribed values, the boundary conditions of problem (13) y (14) to be considered are

$$\begin{aligned} u=\bar{u} &\quad in \quad \Gamma_u\\ p=\bar{p},\quad n_j\tau_{ij}=\bar{t}_i &\quad in \quad \Gamma_p\\ u_j n_j=\bar{u}_n,\quad \left.\begin{aligned}n_j\tau_{ij}g_i&=\bar{t}_1\\ n_j\tau_{ij}s_i&=\bar{t}_2\end{aligned}\right\} &\quad in \quad \Gamma_\tau\end{aligned} \quad (15)$$

Where the boundary $\partial\Omega$ of the domain Ω has been split in three disjoint sets: Γ_u, Γ_p where the Dirichlet and Neumann boundary conditions are imposed and Γ_τ

where the Robin conditions for the velocity are set. In above vectors g, s span the space tangent to Γ_τ. In a similar way, the boundary conditions for (14) are defined

$$\psi = \bar{\psi} \quad in \quad \Gamma_u \tag{16}$$

Finally, initial conditions for the problem to be considered are

$$u = u_0 \quad on \quad \Omega, \qquad \psi = \psi_0 \quad in \quad \Omega \tag{17}$$

where $\Gamma_0 = \{x \in \Omega | \psi_0(x) = 0\}$ defines the initial position of the free surface between the two fluids.

FIC STABILIZED PROBLEM

It is well known that the finite element (FEM) solution of the incompressible Navier-Stokes equations may suffer from numerical instabilities from two main sources. The first is due to the advective character of the equations which induces oscillations for high values of the velocity. The second source has to do with the mixed character of the equations which limits the stability of the solution to the satisfaction of the well known inf-sup condition. The stabilization technique used in this work is based on the FIC (Finite Incremental Calculus) method presented in (Oñate and García, 2001; Oñate et al, 2004; García et al, 2005; Oñate et al, 2006).

The stabilized FIC form of the governing differential equations (13) and (14) can be written as

$$\underline{r_{m_i} - \frac{1}{2} h_{m_{ij}} \frac{\partial r_{m_i}}{\partial x_j}} = 0, \quad \underline{r_d - \frac{1}{2} h_j \frac{\partial r_d}{\partial x_j}} = 0, \quad \underline{r_\psi - \frac{1}{2} h_j \frac{\partial r_\psi}{\partial x_j}} = 0 \tag{18}$$

The boundary conditions for the stabilized problem are written as

$$\begin{aligned} u &= \bar{u} \quad in\,\Gamma_u \\ p = \bar{p} \quad & \underline{n_j \tau_{ij} - \frac{1}{2} h_j n_j r_{m_i}} = \bar{t}_i \quad in\,\Gamma_u \\ u_j n_j = \bar{u}_n, \quad & \underline{n_j \tau_{ij} g_i - \frac{1}{2} h_j n_j r_{m_i} g_i} = \bar{t}_1 \quad in\,\Gamma_u \\ , \quad & \underline{n_j \tau_{ij} s_i - \frac{1}{2} h_j n_j r_{m_i} s_i} = \bar{t}_2 \end{aligned} \tag{19}$$

The underlined terms in equations (18) and (19) introduce the necessary stabilization for the numerical solution of the Navier Stokes problem (Oñate and García, 2001; Oñate et al, 2004; Oñate et al, 2006).

Note that terms r_{m_i}, r_d y r_ψ, y denote the residual of equations (13) and (14), this way, as example:

$$r_{m_i} = \frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) + \frac{\partial p}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} - \rho f_i \qquad (20)$$

The characteristic length distances h_j represent the dimensions of the finite domain where balance of mass and momentum is enforced. Details on obtaining the FIC stabilized equations and recommendation for the calculation of the stabilization terms can be find in (Oñate and García, 2001; Oñate et al, 2004; Oñate et al, 2006).

OVERLAPPING DOMAIN DECOMPOSITION

Let us consider next domain decomposition of domain Ω into three disjoint sub domains Ω_3, Ω_4, and Ω_5 in such a way that $\Omega_3 = \bigcup_e \Omega_3^e$, $\Omega_5 = \bigcup_e \Omega_5^e$.

Where Ω_3^e are the elements of the finite element partition $\Omega = \bigcup_e \Omega^e$, such as $\forall x \in \Omega_3^e \middle| \psi > 0$ and Ω_5^e are the elements of the finite element partition such as $\forall x \in \Omega_5^e \middle| \psi < 0$. The geometrical domain decomposition is completed with

$$\Omega_4 = \Omega \setminus \left(\Omega_3 \cup \Omega_5\right) \qquad (21)$$

From this partition let us define two overlapping domains $\tilde{\Omega}_1$ y $\tilde{\Omega}_2$(see Figure 1):

$$\tilde{\Omega}_1 := \text{int}\left(\overline{\Omega_3 \cup \Omega_4}\right), \quad \tilde{\Omega}_2 := \text{int}\left(\overline{\Omega_4 \cup \Omega_5}\right) \qquad (22)$$

Let V_h and Q_h be $V_{h,i} := \left\{ v \in V_h \middle| v_{|\partial\Omega \cap \partial\tilde{\Omega}_i} = 0 \right\}$, $Q_{h,i} := \left\{ v \in Q_h \middle| v_{|\partial\Omega \cap \partial\tilde{\Omega}_i} = 0 \right\}$ the finite element spaces to interpolate velocity and pressure field, respectively.

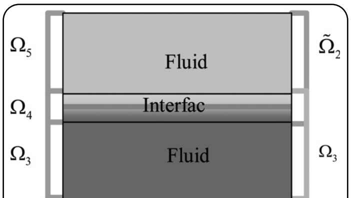

Figure 1. Geometric Decomposition of analysis Domain.

We propose to solve a modified problem of the original FIC stabilized system, written as follows: Given two velocity fields $u_{h,1}^n \in V_{h,1}$, $u_{h,2}^n \in V_{h,2}$, and two pressure fields $p_{h,1}^n \in Q_{h,1}$, $p_{h,2}^n \in Q_{h,2}$, defined in the overlapping sub domains $\tilde{\Omega}_1$ y $\tilde{\Omega}_2$, respectively, in the time t^n and a guess for the unknowns at an iteration $i-1$ at time t^{n+1}, find $u_{h,1}^{n+1,i} \in V_{h,1}$, $u_{h,2}^{n+1,i} \in V_{h,2}$ and $p_{h,1}^{n+1,i} \in Q_{h,1}$, $p_{h,2}^{n+1,i} \in Q_{h,2}$ in time t^{n+1}, by solving next discrete variational problem:

$$\begin{cases} \rho_1 \int\limits_{\tilde{\Omega}_1} \frac{u_{h,1}^{n+1,i} - u_{h,1}^{n}}{\theta \cdot \delta t} \cdot v_h d\Omega + \rho_1 \int\limits_{\tilde{\Omega}_1} \left(u_{h,1}^{n+\theta,i-1} \cdot \nabla\right) u_{h,1}^{n+\theta,i} \cdot v_h d\Omega - \int\limits_{\tilde{\Omega}_1} \nabla \cdot v_h \cdot p_{h,1}^{n+\theta,i} d\Omega + \\ + \int\limits_{\tilde{\Omega}_1} \nabla v_h \cdot \tau_{ij,1} \cdot d\Omega + \sum_{e=1}^{n_e} \int\limits_{\tilde{\Omega}_1^e} \frac{1}{2} (h_m \cdot \nabla) v_h \cdot r_{m,1} d\Omega = \int\limits_{\tilde{\Omega}_1} b \cdot v_h d\Omega \ + \\ + \int\limits_{\Gamma_P \cap \partial\tilde{\Omega}_1} t \cdot v_h d\Omega + \int\limits_{\Gamma_\tau \cap \partial\tilde{\Omega}_1} \left(t_1 g_1 + t_2 g_2\right) \cdot v_h d\Omega \\ \rho_1 \int\limits_{\tilde{\Omega}_1} q_h \nabla \cdot u_{h,1}^{n+\theta,i} d\Omega + \sum_{e=1}^{n_e} \int\limits_{\tilde{\Omega}_1^e} \frac{1}{2} (h \cdot \nabla) q_h \cdot r_{d,1} d\Omega = 0 \\ \left(u_1(x,0), v_h\right)_{\tilde{\Omega}_1} = \left(u_0(x), v_h\right)_{\tilde{\Omega}_1} \\ u_{h,1}^{n+1} = u_{h,2}^{n+1},\ p_{h,1}^{n+1,i} = n\left(\tau_{h,1}^{n+1,i} - \tau_{h,2}^{n+1}\right) n + p_{h,2}^{n+1} - \sigma\kappa \quad en\ \Gamma \end{cases} \tag{23}$$

$$\begin{cases} \rho_2 \int\limits_{\tilde{\Omega}_2} \frac{u_{h,2}^{n+1,i} - u_{h,2}^{n}}{\theta \cdot \delta t} \cdot v_h d\Omega + \rho_2 \int\limits_{\tilde{\Omega}_2} \left(u_{h,2}^{n+\theta,i-1} \cdot \nabla\right) u_{h,2}^{n+\theta,i} \cdot v_h d\Omega - \int\limits_{\tilde{\Omega}_2} \nabla \cdot v_h \cdot p_{h,2}^{n+\theta,i} d\Omega + \\ + \int\limits_{\tilde{\Omega}_2} \nabla v_h \cdot \tau_{ij,2} \cdot d\Omega - \int\limits_{\tilde{\Omega}_2} v_h \cdot b \cdot d\Omega + \sum_{e=1}^{n_e} \int\limits_{\tilde{\Omega}_2^e} \frac{1}{2} (h_m \cdot \nabla) v_h \cdot r_{m,1} d\Omega = \\ = \int\limits_{\Gamma} n \cdot (\tau - p + \sigma\kappa) \cdot v d\Omega + \int\limits_{\tilde{\Omega}_2} b \cdot v_h d\Omega \ + \int\limits_{\Gamma_P \cap \partial\tilde{\Omega}_2} t \cdot v_h d\Omega + \int\limits_{\Gamma_\tau \cap \partial\tilde{\Omega}_2} \left(t_1 g_1 + t_2 g_2\right) \cdot v_h d\Omega \\ \rho_2 \int\limits_{\tilde{\Omega}_2} q_h \nabla \cdot u_{h,2}^{n+\theta,i} d\Omega + \sum_{e=1}^{n_e} \int\limits_{\tilde{\Omega}_2^e} \frac{1}{2} (h \cdot \nabla) q_h \cdot r_{d,2} \cdot d\Omega = 0 \\ \left(u_2(x,0), v_h\right)_{\tilde{\Omega}_2} = \left(u_0(x), v_h\right)_{\tilde{\Omega}_2} \end{cases} \tag{24}$$

For $i = 1,2,3,...$ until convergence, that is to say, until

$$\left\| u_h^{n+1,i+1} - u_h^{n+1,i} \right\|_\infty < tol_u, \quad \left\| p_h^{n+1,i+1} - p_h^{n+1,i} \right\|_\infty < tol_p \tag{25}$$

Where tol_u y tol_p are fixed tolerances.

It is possible to demonstrate that problem (23)-(24) is equivalent to (13)-(14) (Quarteroni and Valli, 1999).

Additionally, it is important to note that the proposed domain decomposition technique, allows to impose boundary conditions on the free surface, and therefore to take into account effects such as the surface tension in the interface, defined by

$$\left[-pI+\mu\tau\right]_{\Gamma}\cdot n=-\sigma\kappa\cdot n \tag{26}$$

where $[\cdot]_{\Gamma}$ notes the pressure jump in the interface and is the surface tension constant of the problem.

The authors have proposed to christen to this new methodology, as a combination of domain decomposition and level set techniques: ODDLS (Overlapping Domain Decomposition Level Set).

ALE FORMULATION

It is of interest in many applications to consider the movement of some parts of the analysis domain. In the mobile parts of the domain is more convenient to use a Lagrangean formulation of the equations and update the spatial discretization every time step. While in the fixed areas of the analysis domain, it is more efficient to use the standard Eulerian formulation. This type of mixed formulation is called "Arbitrary Lagrangian-Eulerian" (ALE) technique (Hirt et al, 1974).

It is possible to obtain a more general formulation of equations (13) and (14) considering next definition of the material derivatives:

$$\frac{D(\cdot)}{Dt}=\frac{\partial(\cdot)}{\partial t}+\left(u_j-u_j^m\right)\frac{\partial(\cdot)}{\partial x_j} \tag{27}$$

Where u_j^m is the relative velocity between the local axes fixed to the fluid particle and the global reference of the problem. This way, it is possible to obtain the ALE formulation of the residuals in (18) as follows

$$\begin{aligned} r_{m_i} &= \rho\frac{\partial u_i}{\partial t}+\rho\left(u_j-u_j^m\right)\frac{\partial u_i}{\partial x_j}+\frac{\partial p}{\partial x_i}-\frac{\partial \tau_{ij}}{\partial x_j}-\rho f_i \\ r_d &= \frac{\partial u_i}{\partial x_i} \qquad\qquad 1\le i,j\le d \\ r_\psi &= \frac{\partial \psi}{\partial t}+\rho\left(u_j-u_j^m\right)\frac{\partial \psi}{\partial x_j} \end{aligned} \tag{28}$$

ADAPTATION OF THE ODDLS METHOD FOR SOLVING MONOPHASE FLOW

It is usual in naval applications to have only one fluid of interest (water). These applications involve biphase flows with density and viscosity rations about 1000 y a

75, respectively. It is important for these cases to adapt the ODDLS technique to solve monophase problems, reducing the computational cost and capturing the free surface with the necessary accuracy and maintaining the advantages of the proposed method. In this case, the computational domain is reduced to the nodes in the water plus those in the air being connected to the water interface. The later nodes are used to impose the pressure and velocity boundary conditions on the interface.

At a computational level, this modification is equivalent to solve problem(23), imposing (29) by means of a local least squares technique.

The proposed monophase adaptation of the ODDLS method has been used in the application example shown in the next section.

CASE OF STUDY

The example of application of the presented technique is the analysis of a high speed boat. The general characteristics of this boat appear in the following table:

Overall length	11.2 m
Molded beam	2.5 m
Displacement	4.9 t
Design velocity	40 kn

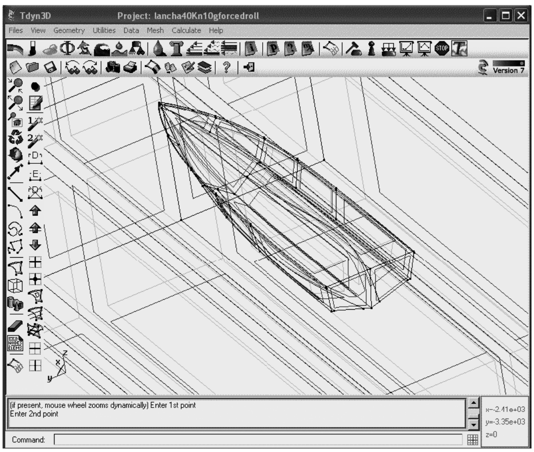

Figure 2. CAD Geometry of The boat Hull.

The geometry of the boat has been defined by means of NURBS patches by the designer, and later exported to GiD-Tdyn software (GiD; Tdyn), where we insert the necessary data for the analyses and mesh generation. The used geometry is displayed in Figure 2. In the mentioned program a computational domain of 45,8 m x 17.6 m x 11.5 m was generated. The referred volume was subdivided in two zones, an internal parallelepiped around the boat, of dimensions 32,8 m x 8,8 m x 6,5 m and an external domain, corresponding to the rest of the volume of analysis. These zones were used for the adaptation of the sizes of elements of the mesh to the analysis requirements. The objectives of this adaptation were two:

Reduce the element size in the neighbor zone of the boat to be able to capture the fluids dynamics phenomena of interest.

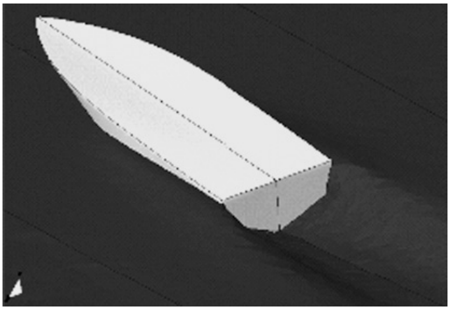

Figure 3. View of fluid Flow in the Stern (V=30 kn).

Create an external zone where the generated waves by the movement of the boat will be damped, reducing therefore the possible effects of bounces in the boundaries of the analysis domain.

This way a nonstructured mesh was generated in the zone near the boat with element size that vary between 0.05 m and.85 m. The resulting mesh of this process contains 420 000 linear tetrahedra, and it was used for all the simulations made in this work. The simulations have been made on salt water using real scale, ignoring the effect of the air in the resolution of the equations of the dynamics of fluids. Each one of the analyses consists of the following phases:

Initial phase: corresponds to the start-up of the simulation, beginning from rest point and arriving to towing speed. This phase is carried out with the ship fixed during 0.5 s of real time.

Towing phase: during 3,5 s of real time an analysis of the towing of the boat is carried out, leaving the boat free to trim and sink.

Rolling phase: during 11.5 s of physical time a forced roll of the boat in different conditions is carried out. Three different towing speeds have been analyzed: 20, 30 and 40 kn.

In the following table a comparative between the steady state situation obtained in the present work during the phase of towing and available experimental data for a scale model is presented:

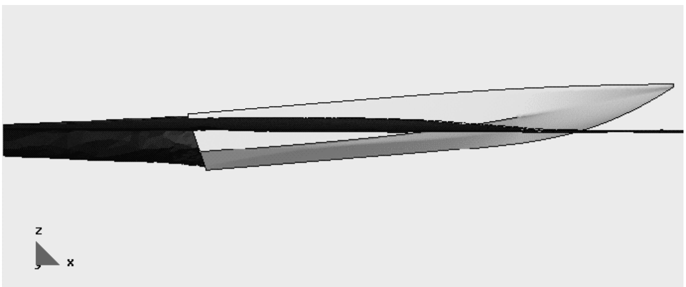

Figure 4. Lateral view of the free surface around the boat (V = 30 kn).

Velocity (kn)	Trim Angle (º)	
	Experimental (model scale)	This Work (Full scale)
20	8.3	7.4
30	5.8	6.3
40	4.1	4.5

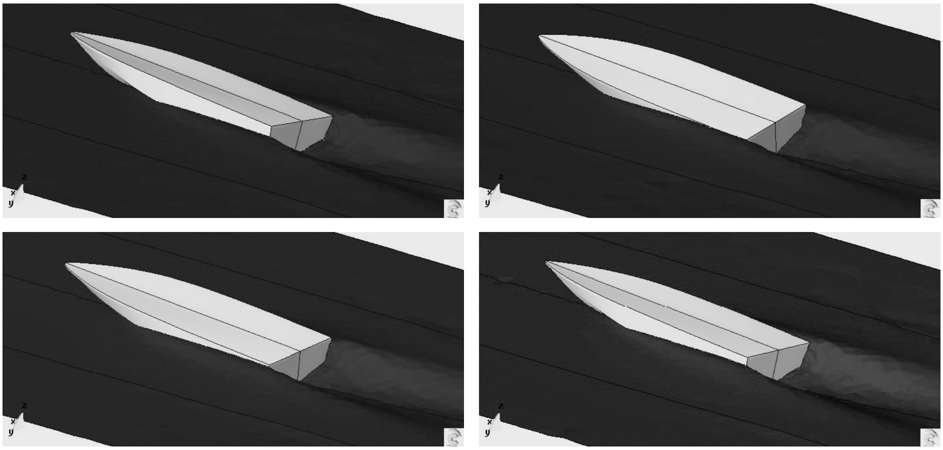

Figure 5. different view of the analysis results during a forced rolling of the boat (V = 30kn, θ = 10º).

Figure 3 shows the flow in the stern of the ship for the case of towing speed of 30 kn, whereas Figure 4 displays a lateral view of the free surface around the boat.

The rolling analyses were carried out for different amplitudes and a for a period near the resonance point of the movement, that has been estimated in T = 1.3 s.

The studied rolling amplitudes are 2, 5 and 10º for each towing speed. In the appendix there are different graphical results from the analyses carried out. Figure 5 shows results of the free surface for case V = 30 kn θ = 10º during a period of the forced balance of the boat. On the other hand, Figure 6 displays different images of the results of the speed field at a dimensionless distance y+ = 65 of the hull, throughout a forced roll period of the boat (case V =40kn θ = 10º). Where $y+= y\cdot\rho\cdot u\tau/\mu$, being y the distance from the hull in the normal direction to the surface. And $u\tau$ the traction in the wall. Finally Figure 7 shows to different mesh cuts from the solution of the equation of level Set in the analysis case corresponding to V = 40 kn θ = 10º. In this image it is possible to appreciate how the method is able to capture the interface between air and water with sufficient accuracy, even with large elements.

The numerical results of these tests are presented in the following tables. In them the amplitude value of the moments induced by pressure and viscous effects are presented:

Amplitude of forced roll 2º

Velocity (kn)	Viscous force moment (N·m)	Pressure moment (N·m)
20	110	2.775
30	170	4.200
40	205	4.880

Amplitude of forced roll 5º

Velocity (kn)	Viscous force moment (N·m)	Pressure moment (N·m)
20	275	6.500
30	450	9.850
40	550	13.000

Amplitude of forced roll 10º

Velocity (kn)	Viscous force moment (N·m)	Pressure moment (N·m)
20	280	7.300
30	705	15.600
40	1.235	25.000

The results of the analyses show a clear influence of the speed in the moments that the fluid exerts on the boat.

From the two calculated components of the moment, the one corresponding to the integration of the pressure is practically in the same phase as the movement, being this contribution of the viscous efforts the unique one that causes the damping effect to the balance movement. As has already been seen in similar studies (García et al, 2005) the increase of the effect of the viscous forces is responsible for the increase of the damping effect of roll movement with the increase of boat speed. On other hand, it is important to note that moments due to pressures has a significant component due to dynamic effects. This is an expectable result due to the high velocity developed by the boat.

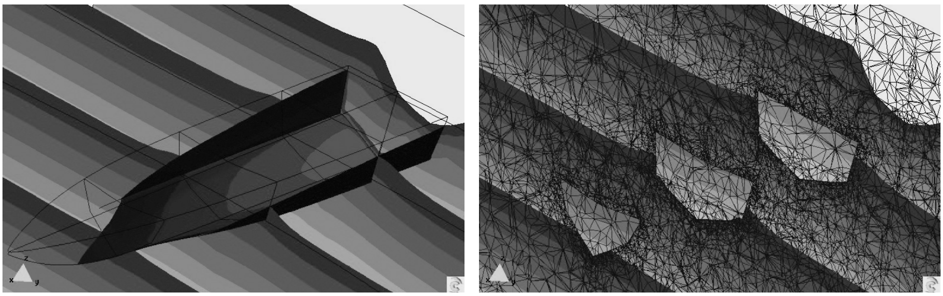

Figure 6. View of Level Set solution over the analysis mesh (level set) (V = 40 kn, θ = 10º)

CONCLUSIONS

The present work shows a new methodology for the analysis of problems with free surface denominated ODD Level Set. This methodology is based on application of domain decomposition techniques and allows increasing the accuracy of the free surface capturing (level set equation) as well as solving governing equations in the interface between water and air. The greater accuracy in the solution of the interface between the fluids allows the use of non-structured meshes, as well as the use of larger elements in the free surface. In addition, the method can be simplified by solving only one of the two fluids, which allows increasing the efficiency in those cases where the effect of one of the fluids can be neglected.

The proposed methodology has been integrated with an ALE algorithm for the treatment of the ship movement and has been applied in the analysis of the towing test and forced roll of a high speed boat. The satisfactory result of the qualitative analysis of the application study shows the capability of the presented methodology for studying this kind of problems.

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REFERENCES

E. Oñate, J García (2001): A finite element method for fluid-structure interaction with surface waves using a finite calculus formulation, *Comput. Meth. Appl. Mech. Engng*., Vol. 191, 635-660.

E. Oñate, J. García y S. Idelsohn (2004): *Ship Hydrodynamics. Encyclopedia of Computational Mechanics*. Eds. E. Stein, R. De Borst, T.J.R. Hughes. John Wiley & Sons.

J. García Espinosa, E. Oñate and J. Bloch Helmers (2005): Advances in the Finite Element Formulation for Naval Hydrodynamics Problems. *International Conference on Computational Methods in Marine Engineering* (Marine 2005). June, Oslo, Norway.

R. Codina (2001): Pressure stability in fractional step finite element methods for incompressible flows, *Jnl. Comp. Phys*., Vol. 170, 112-140.

P-L Lions (1996): *Mathematical Topics in Fluids Mechanics, Vol. 1*. Oxford Lecture Series in Math. and its Appl 3.

J. A. Sethian and P. Smereka (2003): Level set Methods for Fluid Interfaces, *Annu. Rev. Fluid Mech*. Vol. 35, 341-372.

S. J. Osher and J. A. Sethian (1988): Front Propagating with Curvature Dependent Speed: Algorithms Based on Hamilton-Jacobi Formulations, *J. Comput. Phys*. Vol. 79, 12-49.

S. J. Osher and R. P. Fedkiw (2001); Level set Methods: an Overview and Some Recent Results, *J. Comput. Phys.* Vol. 169: 463-502.

R. P. Fedkiw, T. Aslam, B. Merriman and S. J. Osher (1999): A non-Oscillatory Eulerian Approach to Interfaces in Multimaterial Flows (the Ghost Fluid Method), *J. Comput. Phys.* Vol. 154: 393-427.

Hirt, C.W., Amsden, A.A., Cook, J.L. (1974): An Arbitrary Lagrangian-Eulerian Computing Method for All Flow Speeds, *Journal of Comp. Physics*, 14, 227-253

A. Quarteroni, A. Valli, (1999): *Domain Decomposition Methods for Partial Differential Equations*, Oxford Num. Math. and Scien. Comp.

E. Oñate, A. Valls, J. García. (2006): FIC/FEM formulation stabilizing terms for incompressible flows at low and high Reynolds numbers. *Comp. Mech.* 38, 440-445.

GiD. The personal pre/postprocessor User Manual. Available to download at http://www.gidhome.com.

Tdyn. Theoretical Background and Reference Manual. Available to down-load at http://www.compassis.com.

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HABITABILITY AND PERSONAL SPACE IN SEAKEEPING BEHAVIOUR

J. M. Riola[1], M. García de Arboleya[2]

ABSTRACT

The comfort and the well being on board from small sailing boats to huge passengers ships is the focus of this article that describes the factors directly relationated with the assessment of seakeeping performance of a ship in a specified sea environment. In a recent reference is estimated that nearly 10 million people travel each year on more than 230 cruise ships worldwide. So, the increase of comfort level is one of the naval architecture main tasks.

In recent years the development of high-speed craft HSC has been significant. Not only are the dimensions of the vessels increasing, but also service speeds and expectations of performances tend always to increase. Furthermore, it becomes also more common that HSC operate along routes with harsh weather conditions.

Therefore, the issues of operability, hydrodynamic loads and comfort are very important in the research being carried out in the HSC area. The construction of a new modern HSC is a huge investment for the ship owner; he needs to be sure about the passengers comfort level. The assessment procedure requires the pre-

Figure 1. Sailing boats.

Figure 2. HSC.

[1] Doctor Ingeniero Naval, Universidad Politécnica de Madrid (josemaria.riola@upm.es), Nuestra Señora de la Almudena 5, 28250, Madrid, Spain. [2] Psicopedagoga, RGA Psicopedagogía (Myriam@rga-psi.es), Puerto de los Leones 2, 28220, Majadahonda, Spain.

diction of transfer functions for different speed and headings for each ship response. These transfer functions are combined with the appropriate spectral formulation based on the sea characteristics. Also the paper emphasizes in the main psychological problems of the passengers on board due to the fatigue and sickness. This study is based on the ship experience and model tests carried out at Ship Dynamics Laboratory in Canal de Experiencias Hidrodinámicas de El Pardo, CEHIPAR (Riola, 2004).

Keywords: *Seakeepiong, Habitability, Motion Sickness, Assessment, Ship Design*

INTRODUCTION

Anacharsis, brother of Caduides the king of the Scythians, was a philosopher who travelled around the East Mediterranean and Black Sea in the 6th century BC. Their contemporaneous Greeks wrote that he exhorted moderation and good criteria in everything he said. As a seaman, he travelled in different sea conditions and he had the best reference about seasickness "people may be divided into three classes; the living, the dead and the seasick".

Many years from then, Luis Llobera de Avila (Llobera de Ávila, XVI Century), an Emperor Carlos I medicine doctor in the XVI century, accompanied the Spanish king in all their sailings and due to his experience, he advises to avoid sickness problems "to eat little and to smell some days seawater but without seeing it". Avoiding discussions about Llobera's remedies, focussing on the unpleasant experiences on the people on board due to ship motions, this is one of the task performances more delicates to the actual naval architecture designs. Bad weather experiencies (Piñero et al, 2004) are normal in all types of ships but this task is mainly imprtant in the pasenger vessels world. As the philosopher Publiano said "*Improbe Neptunum accusat, qui iterum naufragium facit*" but inherent to the sealife is the unpredictability of weather conditions and the subsequent induced motions at sea.

The stressor crew conditions can be divided in the physical environment ones and the conditions of the task itself. Physical stressors include noise, extremes of temperature, vibration, physical isolation, threat of failure or injury, etc. Stressful task conditionds include time pressure, multiple demands, sleep deprivation and fatigue.

Figure 3. Merchant ship in rough sea.

The seakeeping habitability assesment can be used to improve ship and equipment design and lead to enhanced vessel effectiveness, performance and mainly the safety on board. The ship motions limit not only the passengers, the crew is affected to perform essential functions or not essential but as important as the food preparation and the comfort on board (Riola et al, 2004) is a complex topic the human responses will determine the vessel reputation. Designers always pay attention to feedback provided by operators of exinting ships because these experiences can be considered as important lessons learnt for future designs.

But every effect in ship design is related to other one, for example larger vessels are more comfortable than smaller ones of similar configuration due to the the waves become relatively smaller (Riola et al, 2004). Basic to any seakeeping discussion is the contradictory betwen the roll period and the initial intact stability, so the greater stability, the faster roll will appear and a vessel with dangerously low stability will feel very comfortable but it is the main cause of many disasters yearly, so the architecture design has foccused on determining the acceptable stability in order to achieve the slowest roll period.

A normal passenger ship has a natural rolling period that tends to be the same as the period of waves developed by winds in the range of 20 to 30 knots. The main objective of the naval architecture designer should be to minimise the ship degradation and ensure the safety of passenger on board.

T e seakeeping performance can be defined from the habitability point of view of motions and accelerations are below specified levels (Girón et al, 2004). Sample wave statistics are shown in the next figure for the winter season averaged over the North Atlantic. The relation is between significant wave high to occurrence per cent.

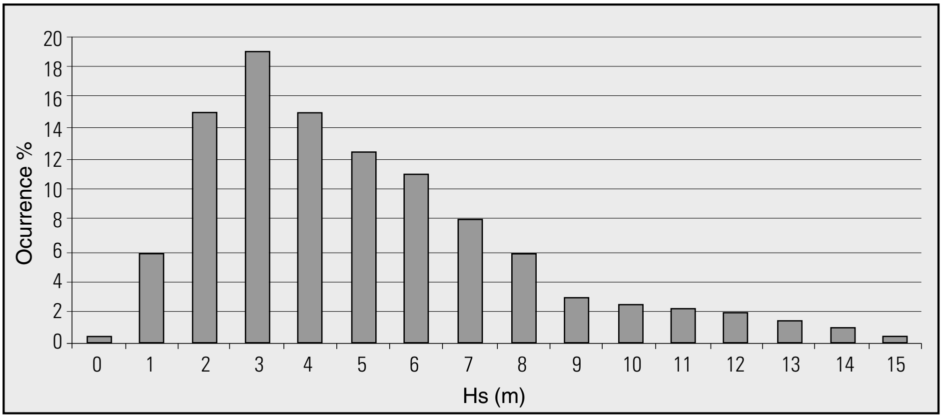

Figure 4: Hs versus occurrence.

PHYSIOLOGY

Three main planes to indicate head and body orientation are used: the coronal, sagittal and transverse planes. The intersection of the mid-sagittal plane and mid-coronal plane forms the spinal axis, yaw is the the rotation about this axis. The rotations about the intersections of the mid-frontal plane and mid-sagittal plane with the mid transverse plane are called pitch and roll. These three rotations are the references of the human body.

In humans, movement through the environment is inferred by three principal sensory systems: the visual sense and the two components of the vestibular system of the inner ear. The human vestibular system is the inertial system that detect and measure the six d.o.f., and it is located in the labyrinth at each inner ear and consists in two main organs, the semicircular canals for detecting angular acceleration and the otolith organs.

Figure 5. Wave impact.

The vestibular apparatus has two otolith organs called utricle and saccule, both with a two layer structure and a sensory cell base, so the otoliths provide linear motion sensation. The main tasks of this system are to enhance the perception of spatial orientation and self-motion, the posture control and to minimize the retinal motion during the head movements.

Motion sickness or kynetosis in the sickness associated to motion, is a term to describe the discomfort and associated emesis, breathing irregularities, warmth, disorientation, pallor and vomiting. According to the mismatch theory, the cause of motion sickness is that the vestibular apparatus provides the brain with information about self-motion that does not match the sensations of motion generated by visual system. Receiving contradictory information or conflicting inputs from two different organs; eyes, the vestibular system and the proprioceptive receptors in the tendons and muscles joints.

Motion sickness is induced by body vibrations at the frequency range between 0.1 to 0.5 Hz. The vertical oscillations are the principal provocative stimulus at sea and their effects are greatest between 0.125 and 0.25 Hz. Due to the verti-

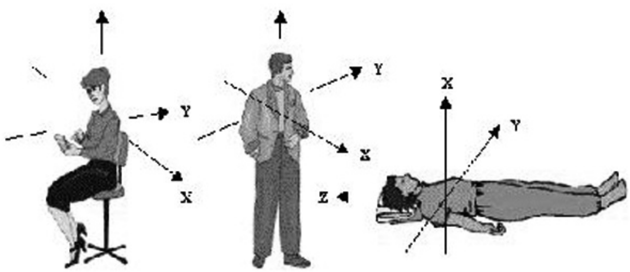

Figure 6. Human axis

cal acceleration in many ships is closer to 0.2 Hz or a roll rate of 5 seconds, this is the sensitivity problem to avoid. Of course, and dependig of the susceptibility individual characteristics, multiple factors have influence in the motion sickness; frequency, intensity, direction and motion duration, activity, food, smell and ambient conditions. Children younger than 2 years are rarely affected but susceptibility rapidly increases peaking between 4 and 10 years old and then gradually declining. Females tends to be more susceptible. Recent ingestion of food, particularly dairy products and foods high in sodium, protein or calories has been associated with increased susceptibility.

Nausea and vomiting are the most common complaints of motion sickness and are mediated by central neurotransmitters. In response to visual and vestibular input, increased levels of dopamine stimulate the medulla oblogata's chemoreceptor trigger zone, which in turn stimulates the vomiting center within the reticular formation of the brain stem. Te vomiting center is also directly stimulated by motion and by high levels of acetylcholine. Therefore, most drugs that are used to prevent or ameliorate motion sickness target these neurotransmitters. Commom drugs fall into three classes: antidopaminergics, anticholinergics and antihistamines.

Alternative medicine remedies are becoming popular, so the most popular herbal preparation for nausea is the ginger root in capsules or tea infusion, but other remedies with apricot juice, carrot juice, unroasted pumpkin, parsley or peppermint tea are recommended too. In a recent trip to Asia learn that the oriental non pharmacologic remedies are based on the acupressure. So the pressure is applied to the P6 acupunture point on the pericardial meridiam, located about 3 centimeters from the distant palmar crease between the palmaris longus and flexor carpi radialis tendons. My experience did not find the preventing evidence, perhaps due to an insufficient pressure stimulation of the P6 point or simply this remedy is a placebo. Researchers and surveys have found that up to 100% of ship passengers become seasick under rough conditions.

PERSONAL SPACING

The anthropologist Edward T. Hall was the precursor of the personal distance studies, the relations between the person and the bubble space surrounding us into which another may not introduce without causing arousal and anxiety. He describes (Hall, 1966) how this space can be used and affect our behavior in a public location. The way to use the personal spacing has an enormous influence in the capacity to relationship with others.

Each person has his own territory zones and react of different way in case of invasion. Our manner to defense our space and entering in the others are an integrative part of our relationship mode. Into a crowd, as occurring in many transports, this space is invaded continuously, as example in a underground top hour.

Hall is normally associated with "proxemics", the study of the human use of space within the context of culture and developed a theory arguing the human perceptions of space, although derived from sensory apparatus that all humans share but molded and patterned by their culture. So, differing cultural frameworks defining and organizing space, which are internalized in all people at an unconscious level, can lead to serious failures of communication with different behaviors that initially expected by crew members.

All we have territorial necessities and it is possible to define them in four areas that grow up in the same way that our privacy is decreasing; the intimate, personal, social and public:

— The intimate space is the closest bubble of space surrounding a person. Entry into this space is acceptable only for closest friends and intimates. This distance goes until 30 or 45 cm. At this distance, we are conscious about the others presence, so if this proximity is not waited, the result is a uncomfortable situation.
— The personal distance goes from 45 cm to 120 cm, where is the physical domination limit. This area is the normal one in personal conversations.
— The social distance, 120 to 210 cm, is used in the most used in commercial transactions and the main contact is the visual. This distance permit us certain protection.
— The public distance, 3 m and more, is the maximum extension of our territorial limits. It corresponds with conferences, speeches, low formal meetings, etc.

The naval architecture needs to project taking in account the personal spacing as a normal factor into the habitability passenger study and in ferry ships, in special, the cross-cultural passenger characteristics. Of course, we can not forget that in rough weather conditions the passenger behavior is almost degraded and the personal spacing sensitive is completely affected.

SEAKEEPING PERFORMANCE ASSESSMENT

The seakeeping performance assesment of a ship is mainly related to the weather conditions, the manoeuvring and navigation conditions, the wave responses of the ship and the required seakeeping criteria for the safety and well being of passengers and crew (Girón et al, 2005). Lateral and mainly the vertical accelerations are the most important factors in the seakeeping performance (Girón et al, 2001). The effect of the vertical accelerations on human bodies is the main cause of sickness and the International Standard provides discomfort boundaries as a function of acceleration levels, frecuencies and duration of exposure. To date of seaway performance calculations, human performance is often defined by parameters and it is a good start for comparisons between designs. Our side needs a research continuation into a fuller definition of human performance that includes, fatigue effects and cognitive performance. Shipboard tasks cover a wide range from those that are mainly manual to those that are mainly mental, and are thus defined by different combinations of all factors. The election of a criteria to know the ship seakeeping performance can vary vastly depending of the ship type but looks logic that in a passenger ship the low porcentage of passengers getting seasick is the main comfort objective. But its more critical to know the crew operatibility due to the lack of safety. In the next table a limited criteria for vertical acceleration is presented.

Limiting criteria for vertical acceleration (RMS)	
0.02 g	Passengers on a big cruise liner
0.05 g	Passengers on a ferry
0.10 g	Normal work for the crew
0.15 g	Heavy work for adapted crew
0.20 g	Ligth work for adapted crew
0.275 g	Simple works

Figure 7. Work limiting criteria.

The International Standard ISO 2631-1 "Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration" (ISO Standard 2631-1, 1997) defines methods of quantifying whole-body vibration in relation to human health and comfort, the probability of vibration perception and the incidence of motion sickness.

The standard defines a motion sickness dose value MSDV such that higher values to a greater incidence of motion sickness where there are two alternative calculating methods depending of the exposure period. If the motion measurements are approximately constant in a short period, where a_w is the square of the measured root mean square z-axis acceleration and T_0 is the exposure register duration, the used formula to obtain the MSDV is:

$$MSDV_z = a_w \; T_0^{1/2}$$

If the motion measurements corresponding to the full period or close, a_w is the frequency-weighted acceleration in the z direction and T is the period, the MSDV can be obtained with the following expression:

$$MSDV_z = \left\{ \int_0^T [a_w(t)]^2 \, dt \right\}^{0.5}$$

Of course, the reactions depending of many factors as human propension, type of activity on board, if reading, etc. The percentage of people who may vomit can expressed by:

$$PV = K_m \, MSDV_z$$

Where K_m is a constant which vary according the exposed population. The following table presents the comfort habitability sensations respect to the exposed accelerations:

Habitability accelerations (RMS)	
< 0.315 ms^{-2}	Not uncomfortable
0.315 – 0.63	A little uncomfortable
0.5 – 1.0	Fairly uncomfortable
0.8 – 1.6	Uncomfortable
1.25 – 2.5	Very uncomfortable
> 2 ms^{-2}	Extremely uncomfortable

Figure 8: Habitability comfortable

The ship motions effects on human performance could be defined in terms of these five factors:

— MII: Motion Indiced Interruptions
— MIF: Motion induced fatigue
— Cognitive performance
— MSI: Motion Sickness Incidence
— Habituation

But usually the main useful parameters refered to motion are the MSI (O'Hanlon and McCauley, 1974) and MII (Graham, 1990). Their definitions have evolved since the 1970s. A mathematical model of MSI was found, as expressed in the following equation:

$$MSI = 100\left[0.5 \pm erf\left(\frac{\pm \log_{10}\frac{a_z}{g} \mp \left(-0.819 + 2.32\left(\log_{10} w_e\right)^2\right)}{0.4}\right)\right]$$

Where *erf* is the error function, a_z is the vertical acceleration averaged over a motion cycle. There is a frequency around 0.167 Hz (1 rad/sec), where the MSI presents a maximum sensitive value.

A Motion Induced Interruption MII is defined as an incident where ship motions become sufficiently large to cause a person to slide or lose balance unless they temporarily abandon their non-seated task to pay attention to keeping upright. The sudden changes in vertical acceleration have a seriously adverse effect on crewmembers to maintain postural stability and carry out their functions whatever they may be. MII is focussed on stumbling, sliding and lift-off, but as general idea it predicts a man will lose balance when the tipping moment exceeds the righting moment provided by the separation of the man's feet. Tipping coefficient is the ratio of the half-stance width to the center of gravity height and it is used to evaluate the probability of tipping per minute. Longitudinal, lateral and vertical forces per unit mass and the sliding, lateral and longitudinal tipping phenomena moments are predicted using the following formulas:

$$F_{longitudinal} = -\ddot{D}_{surge} + g\,\eta_{pitch}$$

$$F_{lateral} = -\ddot{D}_{sway} + g\,\eta_{roll}$$

$$F_{vertical} = -\ddot{D}_{heave} - g$$

$$S = (\ddot{D}_{sway} + g\,\eta_{roll}) - c_f\,\ddot{D}_{heave} \qquad S > c_f\,g$$

$$T = (-\frac{1}{3}h\,\ddot{\eta}_{roll} + \ddot{D}_{sway} + g\,\eta_{roll}) - \frac{1}{h}\ddot{D}_{heave} \qquad T > \frac{l\,g}{h}$$

$$T = (\ddot{D}_{surge} + \frac{1}{3}h\,\ddot{\eta}_{pitch}) - \frac{d}{h}\ddot{D}_{heave} \qquad T > \frac{d\,g}{h}$$

Where *S* is the sliding function, *D* is displacement, h is motion, cf is the frictional coefficient, l is the half-stance width, d is the half-foot length and h is the height of the center of gravity. *STANAG 4154* recommends 35% MSI in two hours or 20% in four, a interruption per minute and a vertical acceleration with a quadratic medium value of simple amplitude of 0.2 g, as operative limits.

If we are designing warships or similar forms a STANAG 4154 is a good tool for seakeeping and habitability characteristics. The majority of the research on human behavior and his consequent parameters of sickness and efficiency on board was carry out by governmental institutions related to the navies and warships. Most of these data are directly applicable to the HSC, so all the obtained highlights are needed in the actual ferry designs.

In the early 1980s, Baitis et al (Baitis, 1984) used a newly developed lateral force estimator LFE to compute motion induced interruptions MII of flight deck crew operations. And in reference (Graham, 1990) in 1990, Graham developed a general lateral force estimator (GLFE) to compute motion induced interruptions MII at any location on the ship. An ad hoc working group of four nations (ABCD) was formed to plan and guide human performance research, starting with series of experiments in the US and UK to measure MII for a range of manual tasks. Crossland and Rich (Crossland, 2000) thus refined the algorithms and criteria for MII. Colwell (Colwell, 2000) reported on the results of shipboard surveys to qualitatively assess a range of effects on performance of a variety of shipboard tasks.

A total of 1,700 booklets of questions were handed to sailors on seven ships in maneuvers off Scotland in February 1997. The sailors were to initially answer a few questions about their specific shipboard assignments. Then at the end of each watch they were to answer questions on the next two pages in the booklet; the first of which addressed symptoms of fatigue and motion sickness and the second, other effects on task performance. At maneuvers ending, an approximate 60% of the booklets were returned. So over 16,000 survey responses to correlate ship motion effects on human factors. Comparisons were made between crewmembers that were susceptible to seasickness and those that were not and between crewmembers that were doing manual tasks and those that were doing cognitive tasks.

A good seakeeping crew reference is the NATO STANAG 4154 on Common Procedures for Seakeeping in the Ship Design Process with the following data criteria:

Recommended criteria
— 20% MSI in 4 hrs
— 1 MII per min
— 35 knots relative wind

Default criteria
— 8º SSA roll
— 3º SSA pitch
— 0.4 g SSA vertical acceleration
— 0.2 g SSA lateral acceleration

Papers given in 2004 in the AVT-110 Symposium on Habitability of Combat and Transport Vehicle began to point the way toward application of human performance models in the design of high-speed vessels. Riola, Esteban y Girón (Riola et al, 2004) introduced the concept of motion filters to address the effects of seasickness.

Vibration as a limit on human performance is also cited in ISO Standard 2631 (ISO Standard 2631-1, 1997). The human body is susceptible to seasickness in the frequency range of 0.05 to 1 Hertz, the range in which ship motion occurs for low to moderate speed ships and vessels. The human body experiences what the ISO standard cites as fatigue decreased proficiency in the frequency range of 1 to 80 Hertz, often the result of structure borne slamming responses and machinery vibration. Miller and French (Miller and French, 2005) reported on a Physiological Stress Index PSI model they developed to estimate the impact of exposure to physical stressors, specifically extreme temperatures and fatigue related to insufficient sleep.

The first step in the seakeeping assesment is to know the hydrodynamic vessel responses related to speeds and headings (Esteban et al, 2005) to the wave excitation loads. The second is to obtain the wave spectra of the operational area to know the motions magnitude. So, the habitability can be obtained based on the probability of motions at acceptable levels. The operational seaway for the ship is decribed by a statistical model, in which the area wave characteristics is known in terms of wave height and wave energy related to frequencies and headings (Recas et al, 2004). In order to compute the motions, first we must compute the forces from any adequate equation.

Normally compute the excitation force, the added mass, and the radiation damping for a vessel as a function of frequency and heading. When the equations of motions are solved for a unit amplitude wave, we obtain a set of quantities called Response Amplitude Operators, or RAOs. These so-called RAOs are the key elements of the seakeeping analysis and they are transfer-function-like operators that give the frequency vessel motion response to the wave amplitude as a frequency function.

Having these RAOs, it is possible to combine them with the sea spectrum to obtain the power spectrum of the ship motion components: surge, sway, heave, roll, pitch and yaw.

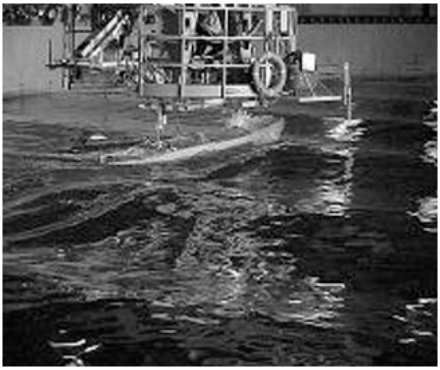

Figure 9. Seakeeping basin.

From the motion components spectrum all the necessary ship motion statistics are obtained and the seakeeping analysis performed.

Using spectral methods we assume that the sea surface is an ergodic, Gaussian random process with zero mean. And the ship can be represented by a linear system that allows the spectral density of any given response to be found by multiplying the incident wave spectrum by the square of the RAO.

The best way to obtain the response amplitude operators RAOs is to carry out model tests in a basin. The amplitudes and phases in the frequency domain and define the response amplitude due to a wave excitation. The tests must be performed with regular wave tests at different headings. The responses of the wave excitation are obtained by superposition of the RAOs and wave spectral density function (Recas et al, 2004). The results must be carried out for a complete set of headings in each ship condition. The amplitudes and phases can be obtained by harmonic analysis using a least squares procedure. The RAOs themselves are of limited use because in reality, the sea is confused with peaks and valleys all over the place. Thus, a sea is normally specified by a spectrum, a function of frequency and heading which gives a measure of the square of the amplitude of a sine wave of this frequency and heading in the sea. So, irregular long crested wave tests must be carried out in order to know the ship behaviour. For the Mediterranean Sea, a JONSWAP wave spectra corresponding to sea state number 3 to 5 with a peak periods from 6 to 8 seconds can be chosen.

Respect to the motions of the six degrees of freedom, the heave, pitch and roll are the most interesting from the seakeeping point of view due to their natural response periods and resonance phenomena. The last necessary step from the motion sickness point of view, is to obtain the vertical and lateral accelerations to obtain parameter comfort data.

HABITABILITY ASSESMENT

The goal of this knowledge of the seasickness is to transfer the information on sailing time to the master on screen to comfort the passengers. According with test data and the experience on ships at sea, people have less tolerance to vertical motions and accelerations in the range of 0.1 Hz to 0.25 Hz o their equivalents in seconds, with a fast sensitivity reduction with higher or lower values.

In the figure 10 can be shown how the master how to reduce the sickness index, in a particular place, slightly modifying the speed or heading of the ship. The two white lines show how the MSI changes when the speed or heading is modified. Of course, this highlight of the results agrees with the real practice because the heading is most influent variable on sickness.

A good presentation to this effect is a polar diagram due to the easy way to control the effect of the speed and headings. A polar diagram is a good assesment for seakeeping performance.

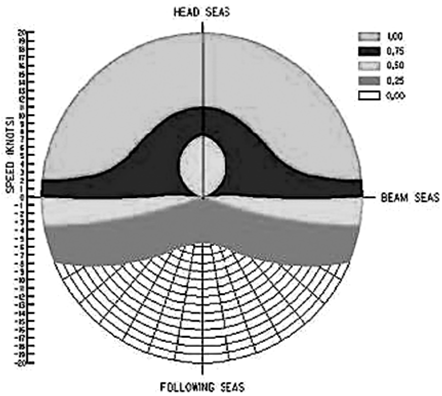

Figure 10. Polar diagram.

This diagram type gives maximum values for each combination of speed, heading and sea state, limiting the area where the ship with this speed and heading can be sailed without exceding any limiting criteria. In the figure 3 is presented a case in the bridge of a passenger ferry in a medium speed in a sea state 4. With the combinations of headings and speeds, a complete manoeuvring set can be obtained and the consequent seakeeping criteria are available in the different sea states of the ship.

CONCLUDING REMARKS

The assesment of the ship seakeeping performance in a operational area requires the prediction of transfer functions for speeds and headings for each response. The transfer functions are then combined with an spectral sea area.

Some evaluation parameters can be used for to developed a seakeeping criteria. A presentation of MSI, MII, ISO2631, GLFE were made. Most of these type of parameters are complementaries and can be appropiated for passenger and crew.

The results must be presented in a esay diagrams to facilitate the cmaster decissions. A good example is the polar one in order to obtain the habitability values for each speed, heading and sea state.

REFERENCES AND BIBLIOGRAPHY

ESTEBAN, S.; RECAS, J.; GIRON, J.M.; DE LA CRUZ, J.M. & RIOLA, J.M. (2005): *A fast Autonomous Scaled Ship for Experimental Seakeeping Control Studies.* IEEE Oceans'05, Brest.

GIRÓN, J.M.; ESTEBAN, S. & RIOLA, J.M. (2001): *Experimental study of controlled flaps and T-foil for comfort improvement of a fast ferry.* International Federation of Automatic Control IFAC Conference on Control Applications in Marine Systems CAMS01, Glasgow.

GIRON, J.M.; ESTEBAN, S. & RIOLA, J.M. (2004): *Actuator and Control Design for Fast Ferry using Seasickness Criteria.* International Federation of Automatic Control IFAC Conference on Control Applications in Marine Systems CAMS04, Ancona.

GIRÓN, J.M.; ESTEBAN, S.; RECAS, J.; ANDRÉS, B.; DE LA CRUZ, J.M.; RIOLA, J.M.; ARANDA, J. & VELASCO, F. (2005): *Overview of Research on Actuators Control for better Seakeeping in Fast Ships.* International Federation of Automatic Control IFAC Conference on Control Applications in Marine Systems CAMS05, Prague.

LLOBERA DE AVILA, L.(XVI Century). *Del regimiento de la mar.*

PIÑERO, J.M.; RIOLA, J.M.; SUCH, J.F. (2004): Historia y actualidad del Mal de Mar. *Revista Marina Civil*, Agosto.

RECAS, J.; GIRÓN, J.M.; ESTEBAN, S.; ANDRÉS, B.; DE LA CRUZ, J.M. & RIOLA J.M. (2004): *CANbus Based System for Course and Ride Control in Fast Ferry Autonomous Model.* IASME Transaction, Issue 2, Vol.1.

RECAS, J.; GIRÓN, J.M.; ESTEBAN, S.; DE LA CRUZ, J.M. & RIOLA J.M. (2004): *Autonomous Fast Ship Physical Model with Actuators for 6 DOF Motion Smoothing Experiments.* International Federation of Automatic Control IFAC Conference on Control Applications in Marine Systems CAMS 2004, Ancona.

RIOLA, J.M.; ESTEBAN, S.; GIRÓN, J.M. & ARANDA, J. (2004): *Motion and seasickness of fast warships,* Research and Technology Organization RTO, Simposium on Habitability of Combat and Transport Vehicles: Noise, Vibration and Motion, Prague.

RIOLA, J.M.; PIÑERO, J.M.; SUCH, J.F. (2004): *Multidisciplinary Study of Seasickness.* 4th International Congress on Technological Innovations and Research. Barcelona.

RIOLA, J.M. (2004): A Seakeeping Laboratory for Experimental Control Tests, *Automation for the Maritime Industries*. Madrid: UNED.

BAITIS, A.E. (1984): *Human Factor Considerations Applied to Operations of the FFG-8 and LAMPS MK III.* ASNE Naval Engineers Journal.

GRAHAM, R. (1990): *Motion-Induced Interruptions as Ship Operability Criteria*. ASNE Naval Engineers Journal, Vol. 102, No. 2.

CROSSLAND, P. (2000): A Method for Deriving MII Criteria. *Transactions of RINA Conference on Human Factors in Ship Design and Operation*, London.

COLWELL, J.L. (2000): NATO Questionnaire: Correlation between Ship Motions, Sea Sickness and Naval Task Performance. *Transactions of the RINA Conference on Human Factors in Ship Design and Operation*, London.

ISO Standard 2631-1 (1997): *Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration*.

MILLER, J. and J. FRENCH. (2005): *Modeling Physiological Stress: the Combined Effects of Physical Activity, Fatigue, and Environmental Conditions.* ASNE HSIS.

HALL, E. (1966): *The Hidden Dimension*. NY: Garden City.

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SIMULATION OF OIL SPILLS AT THE CASABLANCA PLATFORM (TARRAGONA, SPAIN) UNDER DIFFERENT ENVIRONMENTAL CONDITIONS.

J. R. Bergueiro López[1], R. Romero March[2], S. Guijarro González[3] and F. Serra Socías[4]

ABSTRACT

The main objective of this work is the modelization of an oil spill at the Casablanca Platform (Tarragona, Spain) under different environmental conditions and S*imulation Models*. Computerized models used for the simulation of the spill are EUROSPILL, OILMAP, GNOME and ADIOS. Simulation models mentioned above develop a series of *outputs*. First, the most probable trajectory of the spill according to oceanographical and meteorological conditions present during the spill and next hours and the minimum impact time on the coast, if this last arrives to happen. Then, the variation according to the time of the physical and chemical properties of the hydrocarbon mixture. Specifically, the variation of the evaporated fraction of the spilled oil according to time is studied. From the results of the evaporated fraction obtained by the *simulation models*, this fraction is compared with the experimental results obtained by the direct and diffused solar action adjusted, respectively, to a theoretical equation. It is justified because one of the most influent weathering phenomena which affects to a hydrocarbon spill is the evaporation of the volatile fractions, as it modifies as the mixture compo-

[1] Profesor Titular de Ingeniería Química, Universidad de las Islas Baleares (ramonbergueiro@uib.es), Palma de Mallorca, Spain. [2] Profesor Titular de Meteorología, Universidad de las Islas Baleares (Romu.Romero@uib.es), Palma de Mallorca, Spain. [3] Estudiante PhD, Universidad de las Islas Baleares (sguijarro@sbprevencion.es), Palma de Mallorca, Spain. [4] Doctor en Química, Universidad de las Islas Baleares, (kikasesa@yahoo.es), Palma de Mallorca, Spain.

sition as its volume, specially just after the spill or next hours, depending on the kind of mixture, quantity and environmental conditions.

Key words: Oil spill; simulation models; EUROSPILL; OILMAP; hydrocarbons weathering.

INTRODUCTION

Prevention is one of the most important factors for the elaboration of Contingency Plans for hydrocarbon spills, and the importance of this kind of emergency is increasing day by day.

Simulation Models are one of the principal tools, although not the only, which make prevention works in front of a hydrocarbon spill easier.

Spills modelling have got a spectacular advance last years, resulting a great number of commercial computer programmes which allow the simulation of hydrocarbon spills. Generally, these programs have a similar basis and structure.

A series of *input* parameters referred to the spill characteristics and the meteorological conditions during and the hours after the spill, are needed for these programs.

As a result of the spill modelling, a series of *outputs* related to the spill trajectory, the minimum impact time, the impact point and the evaporated, emulsioned and dispersed fraction, just like the remnant quantity of hydrocarbons which will impact to the coast.

METHODS

Simulation models for Hydrocarbon Spills

Simulation Models are computerised systems which allow the estimation of the trajectory and minimum impact time of a hydrocarbon spill depending on environmental conditions by means of algorithms of different complexity. Parallely, a series of results, which are related to the processes of ageing that a hydrocarbon in contact with the environment could suffer, are obtained.

The basic structure of simulation models requires a series of supply parameters of different kind. Firstly, some of the spill parameters required are:

— Date and hour of the spill.
— Geographical coordinates of the spill.
— Type of spill: continuous or discontinuous
— Type of spilt pollutant.
— Quantity of spilt pollutant.

Secondly, environmental parameters:

— Direction and velocity of the currents in the spill area.
— Pattern of winds in the spill area.
— Temperature of the sea and air.

Furthermore, certain models ask for different information about the swell (height and frequency of the waves), presence of ice, water salinity, etc.

On the other hand, simulation models use to incorporate into their system a series of databases referred to the physic chemistry properties of the hydrocarbons, just as Geographic Information Systems (GIS).

Once these supply parameters are inputted, the system generates a series of *outputs* after the simulation as:

- The most probable trajectory of the spill depending on the oceanographic and meteorological conditions of the area.
- Minimum time of impact to the coast, if it occurred.
- Geographic coordinates of the area that is susceptible to be impacted.
- Variation of the quantity of hydrocarbon placed on the coast depending on time.
- Variation of the quantity of evaporated hydrocarbon depending on time.
- Variation of the quantity of hydrocarbon in the water column depending on time.
- Variation of the quantity of hydrocarbon on the sea surface depending on time.
- Variation of the density of the remnant hydrocarbon depending on time.
- Variation of the hydrocarbon viscosity depending on time.
- Variation of the hydrocarbon spill radius depending on time.
- Variation of the hydrocarbon spill thickness depending on time.

As conclusion, simulation models offer important information about the ageing processes of a hydrocarbon mixture in contact to the environment.

Ageing of a hydrocarbons mixture is called to the different processes by the effect of environmental agents as solar radiation, temperature, winds, currents, etc. Consequently, the mixture changes its composition like its physical and chemical properties and the behaviour of the mixture. One of the most important ageing phenomena is the evaporation of the most volatile fractions of the hydrocarbon mixture.

Evaporation is one of the most influent processes during the evolution of the mixture, as for the modifications it produces in the composition as in the volume of the spilt mixture. Evaporation velocity depends on different factors as mixture volatility, which is quite high initially and decreases progressively, temperature and velocity of the air, spill thickness, spill area, turbulence of the sea or the effect of the direct or diffuse radiation.

DEVELOPMENT (APPLICATION AND RESULTS)

Experimental Method

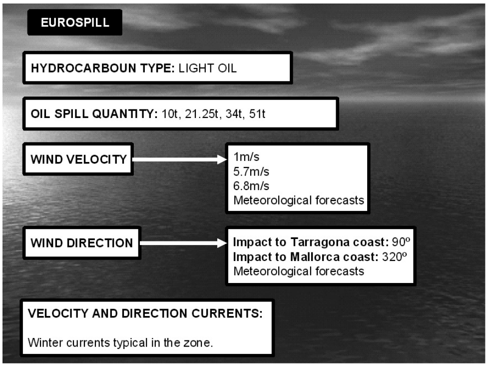
The first objective of this work is doing a series of simulations of crude oil of the Casablanca Platform (Tarragona, Spain), whose geographical coordinates belong to a latitude of 40º 44’ N and a longitude of 01º 26’ E.

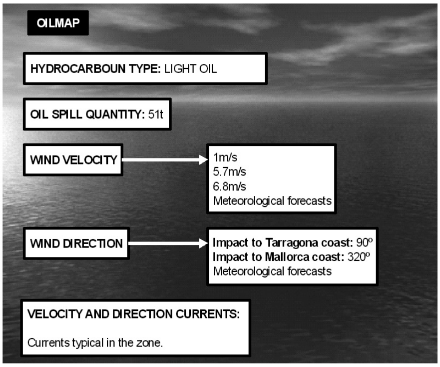
Simulations were done with the EUROSPILL, OILMAP, GNOME and ADIOS models.

Three hypothesis has been considered:

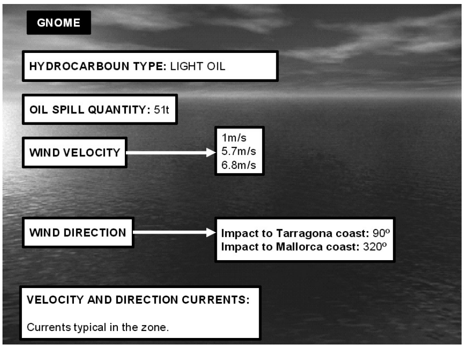
1. Doing the simulations under meteorological conditions that imply the impact of the hydrocarbons to the Tarragona coast.
2. Doing the simulations under meteorological conditions that imply the impact of the hydrocarbons to the Mallorca coast.
3. Doing the simulations during a period of 54 hours with meteorological data obtained from the Meteorological group of the Universitat de les Illes Balears

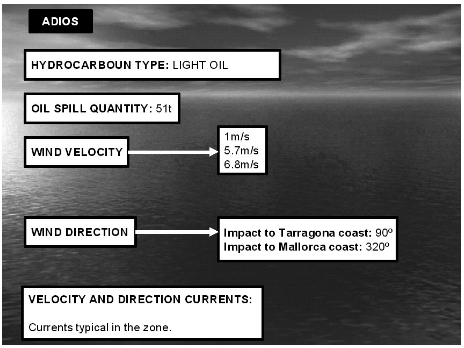
Simulations are done with 10 tonnes, 21.25 tonnes, 34 tonnes and 51 tonnes for Arabian Light oil, very similar to the hydrocarbons of the Casablanca Platform. Simulations are done by Oil Spill Slide Rule since in several cases, the only datum obtained in a short period of time is the density of the remnant hydrocarbons mixture.





Figures 1 and 2. General conditions of simulation for the models EUROSPILL and OILMAP.



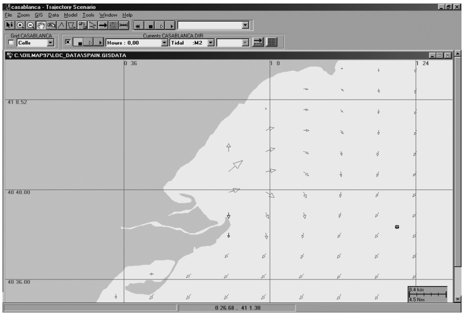


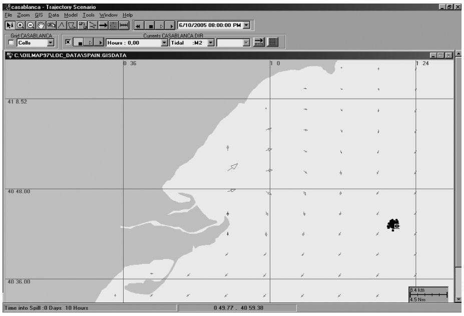
Figures 3 and 4. General conditions of simulation for the models GNOME and ADIOS.

Equally, values obtained from the different simulations were co-related to the equations obtained from the experimental data in environmental conditions under the effect of direct and diffuse solar radiation.

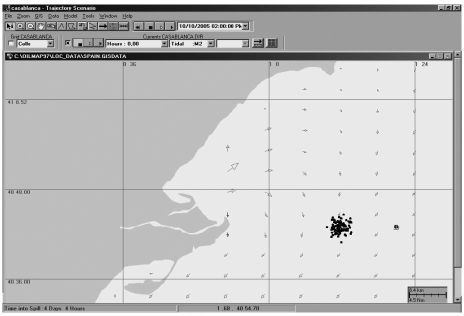
Simulations done with the four programmes mentioned above are shown next in Figures 1, 2, 3 and 4.

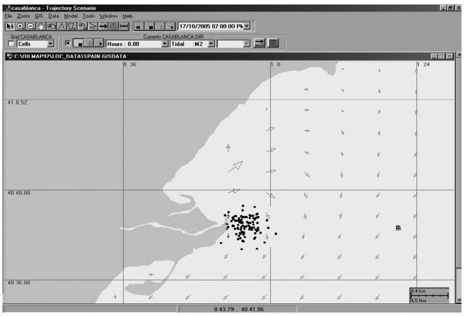
Forty four simulations were done with the four models considering the three hypothetical cases explained above. As an example, one of the simulations did with the OILMAP model is shown, considering a spill of 51 tonnes and a wind of 1 m/s E direction (90º) (Figures 5, 6, 7 and 8).





Figures 5 and 6. Initial position of the hydrocarbon spill and after 10 h, respectively.





Figures 7 and 8. Hydrocarbon spill position after 100 h and 283 h, respectively.

As it can be observed, the model shows the most probable trajectory of the spill depending on the oceanographic and meteorological conditions. Consequently, it is possible to know if the spill reached the coast and, in this case, when and where would impact. So that, in the example, the minimum time of impact is 283 h, reaching the coast at a latitude of 40º 43.3' N and a longitude of 0.5º 56' E

Parallely, a series of results belonging to the ageing processes of the spill are obtained, as well as their behaviour on the sea surface. Concretely, the present work is concentrated on the variation of the evaporated fraction of the hydrocarbon mixture depending on the time necessary to do a comparative study among the different models applied and the theoretical equations.

Concerning the theoretical equations considered, evaporation of a light oil has been studied (Bergueiro and Domínguez, 1996) in the environment, spilt over sea water and over sand of different granulometry, under the influence of several meteorological parameters, just as in the laboratory by *tray evaporation.* Studies show that the experimental data obtained from the evaporated fraction depending on time, complied with Equation 1 for a pre-established wind velocities and direct and diffuse radiation.

$$Fm = a \bullet \ln(1 + bt) \qquad [1]$$

where:
Fm= evaporated fraction (%).
t= evaporating time (min).
a y b= adjustment parameters

When the Marquardt's logarithm (Marquardt, 1963) is applied, the values of the a and b constants are obtained. Their values are shown in Table 1.

Wind Temperature Interval (ºC)	Wind Velocity (m/s)	Direct radiation		Diffuse radiation	
		a	b	a	b
16.8-25.8	1	5.564	0.176	4.156	0.177
16.8-25.8	5.7	6.282	0.155	4.686	0.160
16.8-25.8	6.8	5.896	0.288	4.402	0.229

Table 1. Values of a and b constants depending on the wind velocity and temperature interval.

Comparison of the Evaporated Fraction

Results obtained from the evaporated fraction depending on time were adjusted to a mathematical equation for every one of the studied cases and simulation models used. Subsequently, a comparison among these results and ones from the Equation 1 was done. These comparisons are:

1. Modelling of a spill of 51 t of light oil with a wind velocity of 1 m/s and direction of 90º (Figure 9).

As it can be observed, the best models adjust is by a logarithmic equation like Equation 1, with the exception of the GNO ME model whose adjust is by polynomial equation of second grade.

2. Modelling of a spill of 51 t with light oil and wind velocity of 1 m/s and direction of 320º (Figure 10).

Analogously with the last case, the best adjust of the evaporating results is obtained by a logarithmic equation for all the models with the exception of the GNOME model, whose adjust is a second grade polynomial.

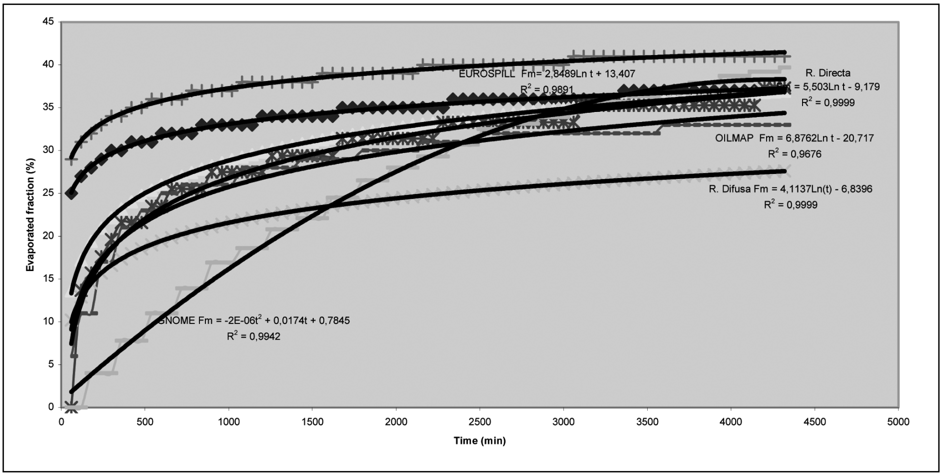


Figure 9. Comparison of the variation of the evaporated fraction depending on time using the different models with a wind velocity of 1 m/s and a direction of 90º.

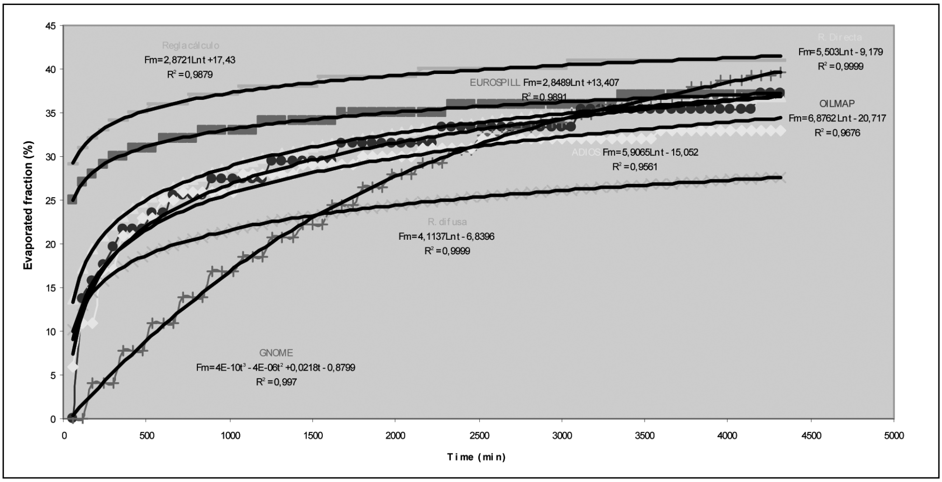


Figure 10. Comparison of the variation of the evaporated fraction depending on time using the different models with a wind velocity of 1 m/s.

3. Modelling of a spill of 51t of light oil with a wind velocity of 5.7 m/s and a direction of 90º (Figure 11).

The results are adjusted to logarithmic equations, with the exception of the EUROSPILL model whose results are adjusted to a polynomial equation of third degree, and the GNOME model which is adjusted to a polynomial equation of second degree.

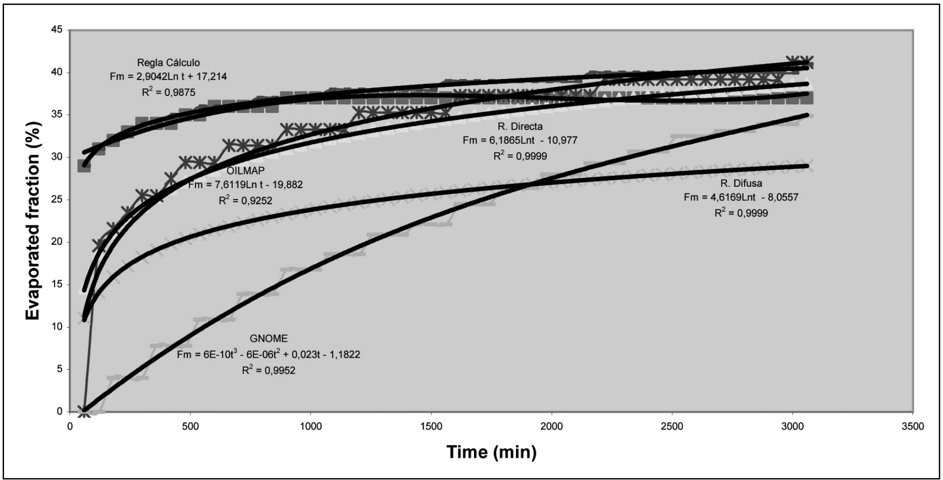


Figure 11. Comparison of the variation of the evaporated fraction depending on time using the different models with a wind velocity of 5.7 m/s.

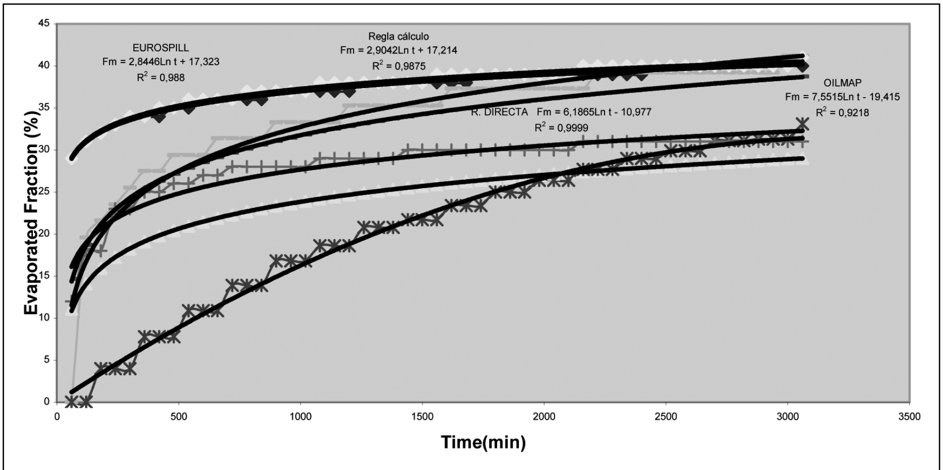


Figure 12. Comparison of the variation of the evaporated fraction depending on time using the different models with a wind velocity of 5.7 m/s.

4. Modelling of a spill of 51t of light oil with a wind velocity of 5.7 m/s and a direction of 320º (Figure 12).

The results are adjusted to logarithmic equations, with the exception of the GNOME model which is adjusted to a polynomial equation of second grade.

5. Modelling of a spill of 51t of light oil with a wind velocity of 6.8 m/s and a direction of 90º (Figure 13).

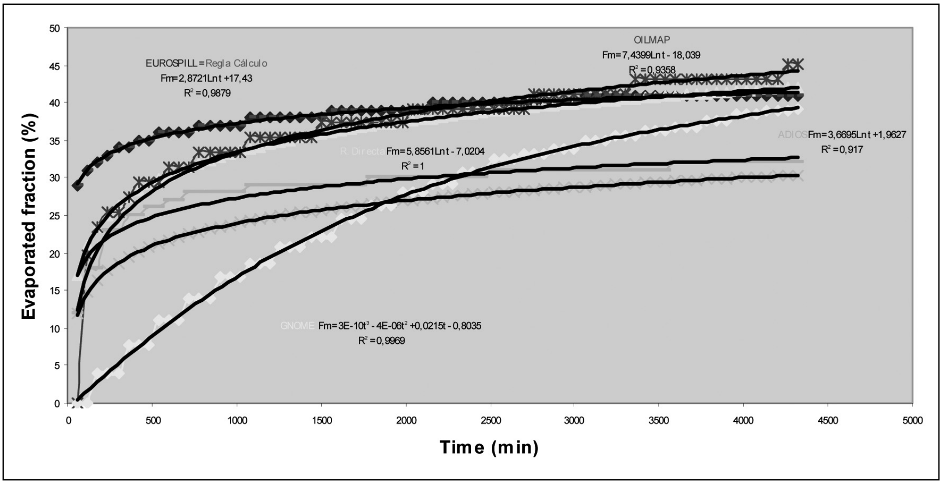


Figure 13. Comparison of the variation of the evaporated fraction depending on time using the different models with a wind velocity of 6.8 m/s.

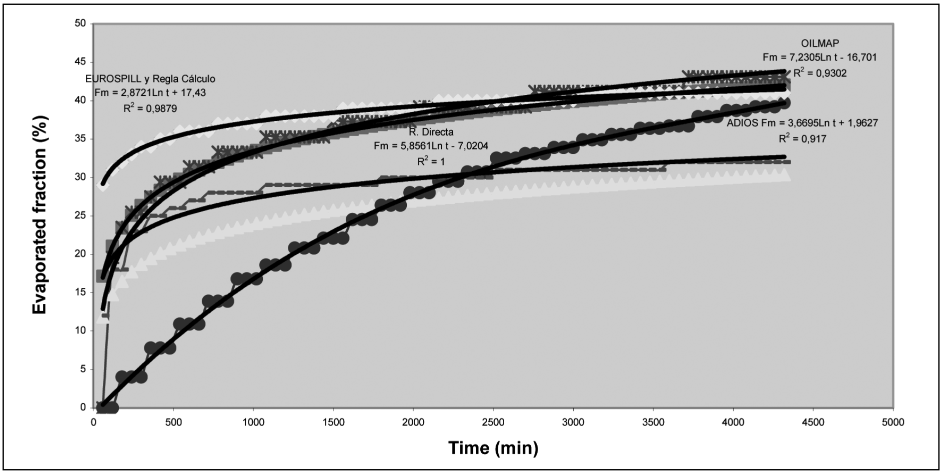


Figure 14. Comparison of the variation of the evaporated fraction depending on time using the different models with a wind velocity of 6.8 m/s.

The results are adjusted to logarithmic equations, with the exception of the GNOME model which is adjusted to a polynomial equation of third grade.

6. Modelling of a spill of 51t of light oil with a wind velocity of 6.8 m/s and a direction of 320º (Figure 14).

The results are adjusted to logarithmic equations, with the exception of the GNOME model which is adjusted to a polynomial equation of third grade.

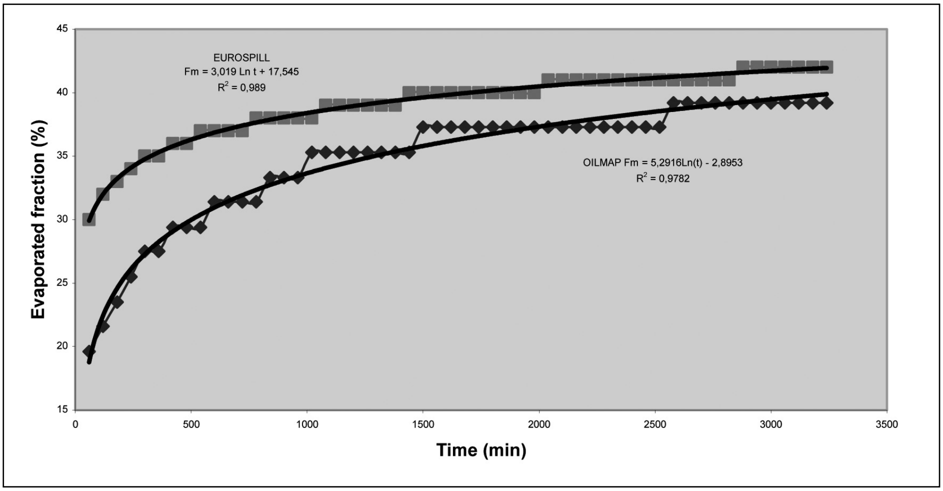


Figure 15. Comparison of the variation of the evaporated fraction depending on time with EUROSPILL and OILMAP models.

7. Modelling of a spill of 51t of light oil with the environmental conditions obtained from the meteorological simulations using the programmes OILMAP and EUROSPILL (Figure 15).

The reason why these two models have been tried is that variable meteorological conditions during the entire process according to the predictions did for the spill area are able to be used.

Both models give good results with the logarithmic equation 1.

Spill Trajectory

From the simulations done with the different models, the probable areas where the spill could impact to the coast were obtained. Simulations with E wind have the impact zone in San Carles de la Ràpita, as Figure 16 and Figures 17 and 18 show.

Simulations with wind direction of 320º, the impact zone is Sa Dragonera (Mallorca) (Figures 19, 20 and 21).

The trajectory followed by the spill, under environmental conditions obtained from meteorological simulations is shown in Figure 22.

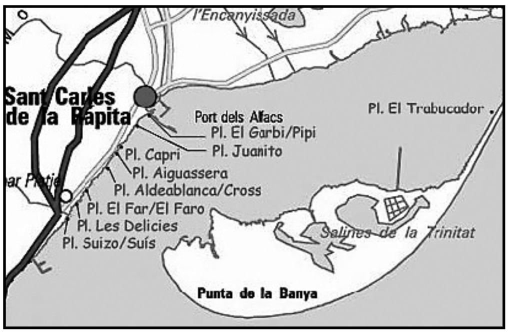
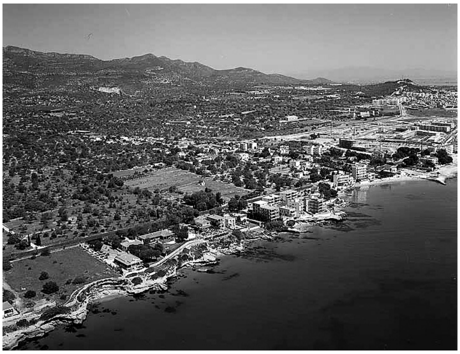


Figure 16. Impact zone of the hydrocarbons at Tarragona.

Figures 17 and 18. Beach Els Eucaliptos, Amposta, Tarragona and Suís, Sant Carles de la Ràpita, Tarragona.

The simulation with the OILMAP model shows that hydrocarbons don't have reached the coast after 54 h. There has been an evaporation of the spilt crude of 39,2% and 31t, with a viscosity of 1849,7 mPa·s, remains on the sea surface.

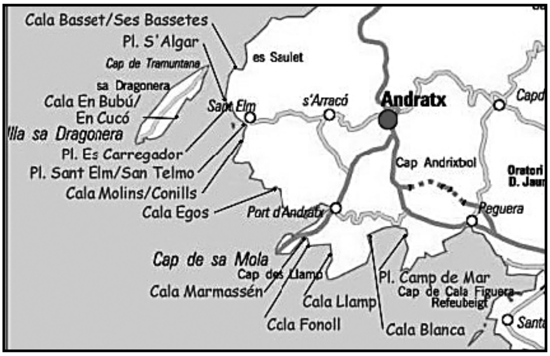


Figure 19. Impact zone of the hydrocarbons in Mallorca Island.


Figures 20 and 21. Sa Dragonera Island, and S'Algar (Andratx).

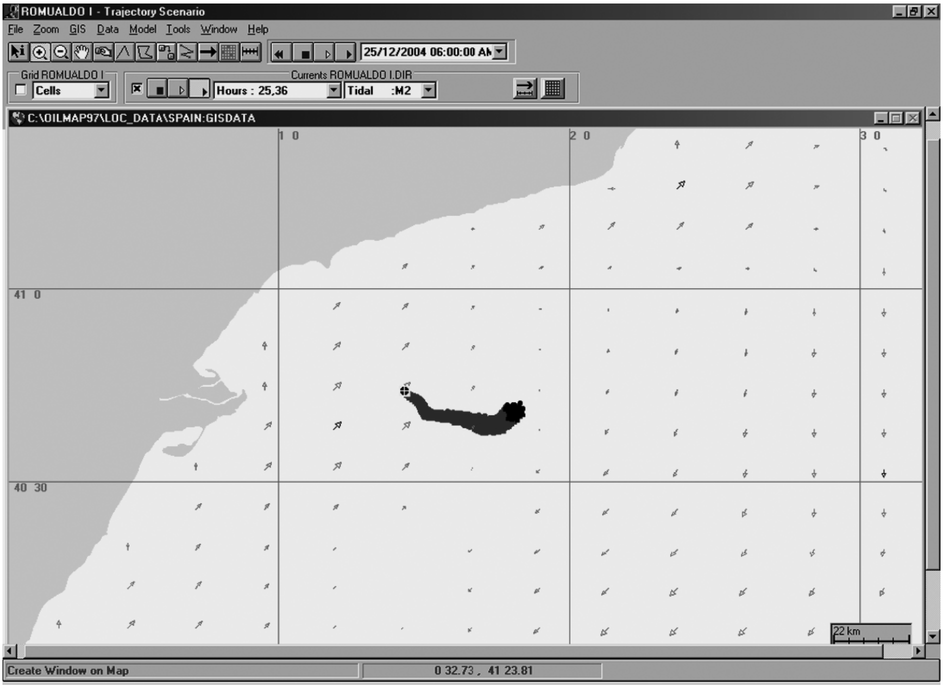


Figure 22. Trajectory followed by the hydrocarbon spill under environmental conditions obtained from the meteorological simulations.

Restoration and Cleaning Costs

Several calculations have been done using the equations suggested by Bergueiro and Moreno (2002). Firstly, the number of workers needed for the cleaning and restoration of Tarragona and Mallorca affected areas have been calculated with a result of 34 days. Next, the number of workers needed resulting 871 for Sant Carler de la Ràpita and 869 for Sa Dragonera.

Finally, the cost of cleaning and restoration has been estimated in about one million and a half euros for both cases.

CONCLUSIONS

1. From the simulations carried out with a spill of 51t under the effect of a E wind, result that hydrocarbons impact to Sant Carles de la Ràpita area after 20 h. During this period of time the 37,00% of the spilt hydrocarbons have been evaporated resting 32,13t on the sea surface, with a density of $0.23 \cdot 10^5$ mPa·s, a flash point of 101,8ºC and a water content of 80%.

Equally, 130t of a mixture of hydrocarbons and water have been placed on the coast.

2. From the simulations carried out with a spill of 51t under the effect of a 320º wind, result that hydrocarbons impact to Dragonera Island (Mallorca) after 87h. During this period of time the 42,00% of the spilt hydrocarbons have been evaporated resting 26,01 t on the sea surface, with a density of 1006 kg/m^3, a viscosity of 0.40·10^5 mPa·s, a flash point of 119ºC and a water content of 80%. Equally, 85t of a mixture of hydrocarbons and water have been placed on the coast.
3. From the simulations carried out with a spill of 51t under the environmental conditions obtained from meteorological simulations, result that hydrocarbons have not impacted to the coast after 54h. During this period of time the 42,00% of the spilt hydrocarbons have been evaporated resting 29,58t on the sea surface, with a density of 1006 kg/m^3, a viscosity of 0.41·10^5 mPa·s, a flash point of 120ºC and a water content of 80%.
4. Plots belonging to the variation of the evaporated fraction versus time, which have been obtained from the different simulation models, have their best adjust as logarithmic equations like $Fm = a \bullet \ln(1+bt)$. This equation gives good results in the evaporation studies done in the environment and in the laboratory. The values of the evaporated fraction versus time obtained with the GNOME model have their best adjust with polynomial equations of second and third grade.
5. The values of the physical parameters obtained by the different models, show variations during the first tours after the spill, whereas at the end of the evaporation, the agreement of these parameters is quite satisfactory.
6. The number of workers needed, time of intervention and the total cost for the cleaning and restoration of both affected zones by the two spills with the next results:

Sant Carles de la Ràpita area:

Estimated time for cleaning and restoring the coast: 34 days.

Number of workers needed: 871.

Cost of the operation: 1.495.756 €.

Sa Dragonera area:

Estimated time for cleaning and restoring the coast: 34 days.

Number of workers needed: 869.

Cost of the operation: 1.489.143 €

REFERENCES

BERGUEIRO LÓPEZ, J.R.; DOMÍNGUEZ LASECA, F. *Evaporación de Mezclas de Hidrocarburos.* Editorial Bilbilis, 1996. ISBN: 84-86682-07X.

BERGUEIRO LÓPEZ, J.R. and MORENO GARCÍA-LUENGO, S. Limpieza y Restauración de Costas Contaminadas por Hidrocarburos. Procedimiento Operacional. Universitat de les Illes Balears. Palma de Mallorca. 2002. Depósito Legal: PM 1.203-2002. ISBN: 699-8769-0.

MARQUARDT, D.M. *An algorithm for Least-Squares Estimation of Non-linear Parameters.* Journal Society Indust. Aptl. Math., Vol. 11, pp. 431-441. 1963.

MODELIZACIÓN DE VERTIDOS DE HIDROCARBUROS EN LA PLATAFORMA CASABLANCA (TARRAGONA, ESPAÑA) BAJO DIFERENTES CONDICIONES MEDIOAMBIENTALES.

RESUMEN

El objetivo principal de este trabajo es el de modelizar un derrame de hidrocarburos en la Plataforma Casablanca (Tarragona, España) bajo diferentes condiciones medioambientales y modelos de simulación. Los modelos informatizados utilizados para la simulación del derrame son EUROSPILL, OILMAP, GNOME y ADIOS. Los anteriores modelos suministran una serie de *outputs*. En primer lugar, la trayectoria más probable del derrame de acuerdo a las condiciones oceanográficas y meteorológicas reinantes durante el derrame y las horas posteriores y el tiempo mínimo de impacto en la costa, si éste último llega a producirse. Además, se obtiene también la variación de las propiedades físicas y químicas de la mezcla de hidrocarburos en función del tiempo transcurrido desde el momento del vertido. Se estudia la variación de la fracción evaporada del hidrocarburo vertido respecto al tiempo. Los resultados de fracción evaporada obtenidos mediante los modelos de simulación se comparan con los resultados experimentales obtenidos bajo la acción de la radiación solar directa y difusa, correlacionados mediante una ecuación teórica. Los estudios de evaporación se justifican debido a que ésta es uno de los fenómenos de envejecimiento más influyentes que afecta a un vertido de hidrocarburos, lo que provoca una modificación del volumen y de la composición de la mezcla remanente.

METODOLOGÍA

Parte experimental

El primer objetivo de este trabajo es el de efectuar una serie de simulaciones de vertidos de crudo de petróleo desde la Plataforma Casablanca (Tarragona, España), cuyas coordenadas geográficas corresponden a una latitud de 40º 44'N y una longitud de 01º 26' E.

Se han considerado tres hipótesis de trabajo:

1. Efectuar las simulaciones bajo unas condiciones meteorológicas que impliquen el impacto de los hidrocarburos en la costa de Tarragona.
2. Efectuar las simulaciones bajo unas condiciones meteorológicas que impliquen el impacto de los hidrocarburos en la costa de Mallorca.

3. Efectuar las simulaciones durante un periodo de 54 horas con datos meteorológicos obtenidos de estimaciones efectuadas por el Grupo de Meteorología de la Universitat de les Illes Balears.

Las simulaciones se efectuaron con 10 t, 21 t, 25 t, 34 t y 51 t para un crudo Arabia Ligero de características muy similares a los hidrocarburos que se obtienen en la Plataforma Casablanca. Se realizaron cuarenta y cuatro simulaciones con los cuatro modelos y considerando los tres casos hipotéticos planteados anteriormente.

El modelo genera la trayectoria más probable del vertido de hidrocarburos según las condiciones oceanográficas y meteorológicas. Consecuentemente, es posible determinar si el vertido alcanzará la costa y, en caso afirmativo, cuándo y dónde impactará.

Costes de limpieza y restauración

Utilizando las ecuaciones propuestas por Bergueiro se ha calculado, en primer lugar, el tiempo necesario para la limpieza y restauración de las zonas de Tarragona y Mallorca afectadas por los vertidos de hidrocarburos, resultando ser de 34 días. Seguidamente se ha estimado el número de personal necesario resultando ser 871 para el caso de Sant Carles de la Ràpita (Tarragona) y 869 para el caso de Sa Dragonera (Mallorca). Finalmente se ha estimado el coste derivado de dicho personal, resultando ser del orden de millón y medio de € en ambos casos.

CONCLUSIONES

De las simulaciones efectuadas con un derrame de 51 t bajo el efecto de un viento Este puro, se obtienen que los hidrocarburos impactan en la zona de Sant Carles de la Ràpita al cabo de 20 h. Durante ese tiempo se ha evaporado un 37% de los hidrocarburos derramados quedando 32,13 t en la superficie del mar, con una densidad de 1005 kg./m^3, una viscosidad de $0,25 \cdot 10^5$ mPa.s, un punto de flash de 101,8 ºC y un contenido en agua del 80 %. Igualmente se han depositado en la costa 130 t de una mezcla de hidrocarburos y agua.

De las simulaciones efectuadas con un derrame de 51 t bajo el efecto de un viento en dirección 320º, se obtienen que los hidrocarburos impactan en la zona de la isla de Dragonera (Mallorca) al cabo de 87 h. Durante ese tiempo se ha evaporado un 42% de los hidrocarburos derramados quedando 26,01 t en la superficie del mar, con una densidad de 1006 kg./m^3, una viscosidad de $0,40.10^5$ mPa.s, un punto de flash de 119 ºC y un contenido en agua del 80 %. Igualmente se han depositado en la costa 85 t de una mezcla de hidrocarburos y agua.

De las simulaciones efectuadas con derrame de 51 t bajo condiciones ambientales obtenidas a partir de simulaciones meteorológicas, se llega a la conclusión que transcurridas 54 h los hidrocarburos no han impactado en la costa. Durante ese tiempo se ha evaporado un 42% de los hidrocarburos derramados quedando 29,58 t en la superficie del mar, con una densidad de 1006 kg./m^3, una viscosidad de 0,41.10^5 mPa.s, un punto de flash de 120 ºC y un contenido en agua del 80%.

Los valores de los parámetros físicos, obtenidos con los diferentes modelos, en las primeras horas del derrame presentan ligeras variaciones entre sí, mientras que en los estadios finales de la evaporación la concordancia de dichos parámetros es bastante satisfactoria.

Se han calculado el número de empleados necesarios, el tiempo de actuación y el coste total de la limpieza y restauración de las dos zonas afectadas por los dos derrames, resultando ser los siguientes. Para la zona de Sant Carles de la Ràpita: tiempo estimado de limpieza y restauración de la costa 34 días, personal necesario 871 y coste derivado del personal 1.495.756 €. Para la zona de Sa Dragonera: tiempo estimado de limpieza y restauración de la costa 34 días, personal necesario 869 y coste derivado del personal 1.489.143 €.

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RECENT STUDIES ON ANTIFOULING SYSTEMS TO ARTIFICIAL STRUCTURES IN MARINE ECOSYSTEM

E. Eguía López[1], A. Trueba Ruiz[2], B. Río Calonge[3], M. A. Girón Portilla[4] and C. Bielva Tejera [5]

Abstract

Any artificial structure in contact with seawater is rapidly coated by a microbiological biofilm, which serves as a base for macro-organisms to grow on. It is known the biofouling phenomenon, as well as the negative consequences that it means for the artificial structures in contact with seawater in form of structural defects and of additional expenses for the companies which develop their work in the marine scope due to the processes of cleaning and prevention, the evolution in the world of the technology of antifouling paintings, once we analysed the serious environmental problems caused by an indiscriminate use of biocides of high toxicity in its composition as they are the organic derivatives of tin compounds made up and of the uncontrolled emission of volatile organic compounds (VOC) to the atmosphere, according to the present environmental norm, has as only aim to develop environmentally innocuous coverings based on water in which extracts of the very same marine world are used as biocides compounds.

Key words: Biofouling, antifouling paints, organic by-products of tin compounds, volatile organic compounds (VOC), environmental norm.

[1] Catedrático de Universidad, Department of Sciences and Techniques of Navigation and Shipbuilding, University of Cantabria (emilio.eguia@unican.es), Santander, Spain. [2] Profesor Ayudante Doctor, Department of Sciences and Techniques of Navigation and Shipbuilding, University of Cantabria, (alfredo.trueba@unican.es), Santander, Spain. [3] Profesora Titular Universitaria, Department of Sciences and Techniques of Navigation and Shipbuilding, University of Cantabria, (belen.rio@unican.es), Santander, Spain. [4] Profesor Titular Universitario, Department of Sciences and Techniques of Navigation and Shipbuilding, University of Cantabria, (alfredo.giron@unican.es), Santander, Spain. [5] Doctorando, Department of Sciences and Techniques of Navigation and Shipbuilding, University of Cantabria (carlos.bielva@alumnos.unican.es), Santander, Spain.

INTRODUCTION

Any artificial structure in contact with seawater is rapidly coated by a microbiological biofilm, which serves as a base for macro-organisms to grow on. This phenomenon, known as biofouling, causes structural problems and its mitigation involves a severe economic outlay for maritime industries.

Biofouling can be defined as *"the undesirable phenomenon of adherence and accumulation of biotic deposits on a submerged artificial surface or in contact with seawater."* This accumulation or incrustation consists of a film composed of micro-organisms affixed to a polymeric matrix created by themselves (biofilm), where inorganic particles (salts and/or corrosive products) may arrive and be retained, as a consequence of other types of fouling developed in the course of the process. This biofilm composed of microorganisms (microbial biofouling or *microfouling*) can originate the accumulation of macro-organisms (macrobial biofouling or *macrofouling*) (Eguía, 1996).

Biofouling is made up of hundred of species such as tubicolous bacteria, protozoan, seaweed, molluscs, bryozoans, cirripeds, polychaetes, ascidians, hydrozoans, etc. These organisms adhere themselves to the substrate developing a fast growth and great reproductive potential, having seen the strategy of the different families in order to obtain the resources that the ecosystem offers, avoiding the competition among them by means of the differentiation of the periods of colonisation, in such a way, that the incrustation begins with the settling of the phytobenthonic organisms during the springtime, to then continue with the adhesion of zoobenthonic organisms (García P, 1996).

Therefore, biofouling accelerates the processes of corrosion of the materials and causes losses in the performance of the structures. These damages take place on movable and stationary structures such as boats, petroliferous or gas platforms, oceanographic investigation implements, thermal energy conversion plants and subaqueous sounding equipment. It also damages maritime cultivation facilities (aquariums, cages, conduits, and pumps) as well as their cultivated organisms. (Yebra et al., 2004)

In ships the friction between the hull and the water increases, which means an increase in fuel consumption (up to 40-50% with low density biofouling) and a decrease in speed and manoeuvrability. The hull of a ship unprotected by antifouling systems, can accumulate up to 150 kg of biological incrustation by square meter during six months in the sea, which in a long tanker with 40,000 m^2 of underwater hull supposes an increase in weight of 6000 metric tons of biological incrustations (OMI, 1999), which means enormous economic losses.

In order to avoid economic losses, as well as an accelerated deterioration of the artificial structures in contact with seawater, different types of protections have been used over time. Among them we must point out the copper coatings that began to be used by the Phoenicians and which continued to be successfully used on wood ships until the 18th century. When iron ships were first built, paints widely known as "patents" in which the copper sulphate acted as a biocide principle began to be manufactured. In 1960 the use of paints in which the composition we could find copper, mercury, arsenic, organic derivatives of tin (organic compounds of tin like tributyltin (TBT) and the trifeniltina (TPT)) spread widely, eventually, they proved to be a real risk for the marine ecosystem.

In the seventies, there was continued use of antifouling paints based on the biocide performance of the organic derivatives of tin, especially tributyltin (TBT); that is why most of the navigation ships covered their hulls with these types of paints, which turned out to be effective and economic.

During the eighties we discovered the consequences on the marine ecosystems from using TBT in antifouling paintings, especially in areas of low water interchange by tidal influence, such as bays or estuaries, where it is specially detrimental to the populations of some invertebrates, molluscs, crustaceans and fish, where serious malformations in some species were detected. As a result of the worries arising from these findings, several countries introduced controls to limit the use of TBT in antifouling paints in small ships. Thus, in 1982, France prohibited the use of TBT in ships with a length inferior to 25 m; Japan, United Kingdom, the United States, Norway, Australia, New Zealand and other countries followed.

At the beginning of the nineties, an OMI resolution recommended governments to ban the use of tributyltin in ships less than 25 m long and restrictions in the leaching process of tributyltin were imposed, having to be inferior to 4 micrograms/cm^2 /day. In countries such as Japan, New Zealand and Australia the use of antifoulings that contain TBT was forbidden.

Since 1997, Japan prohibited the manufacture of antifouling paints containing TBT, with January 1, 2003 as the proposed date for the prohibition of the organic derivatives of tin compound use as biocides in antifouling system, leading to its total prohibition by 2008.

CONSEQUENCES OF THE USE OF ORGANIC DERIVATIVES OF TIN COMPOUNDS SUCH AS BIOCIDES IN ANTIFOULING PAINTS

Generally speaking, all the organic compounds of tin, and especially tributyltin (TBT), are extremely toxic compounds, even at concentrations of only a few nanograms per litre. The organisms of the marine environment (from bacteria to fish) are affected by a wide range of harmful effects from sub-lethal to lethal. Their presence can be seen in alterations in growth, production of anatomical and reproductive anomalies, changes in behaviour patterns, etc. The macroinvertebrates that are the most affected are the molluscs due to their high rate of bioaccumulation and to their low rate of purification. Within these, the most sensitive groups are the gastropods and the bivalves. In other taxonomic categories they follow to them in sensitivity, crustaceans, algae and fish. Nevertheless, no organism has so far shown the sensitivity that characterises neogastropods.

The magnitude of the effects of TBT and the repercussion of the legislation of their use were particularly remarkable in oysters and neogastropods. Specifically, the most devastating effects of TBT in the marine environment were observed on the curly or Japanese oyster, *Crassostrea gigas* and the coastal gastropod *Nucella lapillus* (snail multicoloured). The harmful effects of TBT on *Crassostrea gigas* were what set in motion the beginning of the legislation to control the use of this compound in the formulation of antifouling paints, a fact that is now a milestone in the recent history of environmental protection (Quintela, 2002; Jelic-Mrcelic et al., 2006).

The Bay of Arcachon (Atlantic coast of France) is one of the most important areas for the oyster breeding in the world and its economy depends on the sale both of oyster seeds and of the adults themselves. It produces from 10,000 to 15,000 metric tonnes of Japanese oyster, 10% of the French total production. During the summer season there is a great deal of maritime movement a dense marine occupation, with the number of pleasure ships sometimes reaching 15,000. At the end of the Sixties there began to be observed, occasionally, a thickening of the oyster shells and from 1974 on this was to be seen in all the oyster beds of the bay, affecting between 80 to 100% of the oysters. Between 1971-1986 a series of phenomena took place that severely damaged the oyster breeding in the area, such the appearance of physical anomalies (malformations in the shell characterised by the thickening of valves), reduction in individual oyster growth and drastic fall of the putting. Different studies consistently related these anomalies to contamination by TBT coming from antifouling paints.

The anomalies registered affected the calcification process and comprised the thickening of the shell because of the formation of chambers that contained gelatinous proteins in their interior so that the shell acquired a spherical and unpleasant aspect. The space destined for the body was reduced, which led to the oysters having less flesh on them. Both factors prevented the commercialisation of these bivalves, causing the collapse of oyster breeding from 1977 to 1981. In these circumstances, with a concentration of TBT in water superior to 100 ng/l, the number of oyster breeders was reduced to half and the economic losses ascended to about 150 million dollars. The resulting profound socio-economic crisis caused French authorities to regulate the use of paints with a TBT base in January of 1982, which made is possible to gather a satisfactory number of oysters in summer, after five years of total loss of life of larvae.

The second paradigmatic case of the negative effects of TBT on organisms that, at the outset, were not the object of their action, is that of marine gastropods, and specifically the neogastropods. What has occurred here is the superimposition of masculine sexual characters on the females and which has received the name of *imposex*. In some species, this phenomenon negatively affects the reproductive ability so that, under certain conditions of contamination, the populations of the most sensitive species are doomed to disappearance.

One of the first impacts of exposure to TBT that was described was the masculinization of the females of neogastropods. This phenomenon was detected almost simultaneously in *Nucella lapillus* around 1970 in Plymouth Sound (England), *Nassarius obsoletus* in Long Island (the United States) and in Erinacea Ocenebra in Arcachon (France).

The term *imposex* was coined to denote that superimposition of masculine sexual characters on females. The first evidence of the bond between this phenomenon and the contamination by TBT did not appear until some ten years later. And it was not until the methods of analysis of organic derivatives of tin compounds were perfected that the sensitivity of TBT response became obvious. Multiple later studies have demonstrated that it is a widely extended event and at the present time it has been stated that some 150 species pertaining to approximately 78 geniuses, including the mesogastropods, show imposex.

When the females of *N. Lapillus* are exposed to TBT, their takes place a masculinization proportional to the dose of polluting agent. A penis and a vas deferens begin to form. The vas deferens extends towards the oviduct and can even actually block it, making it impossible for the egg capsules to come out so that the females functionally become sterile. In extreme cases the bursa copulatrix can even be substituted by a prostate. Finally, the accumulation of the aborted egg capsules causes a trauma that leads to the death of the animal, which is why in highly affected populations there is a low proportion of females.

Both this lessening of the number of females in the populations and, mainly, the sterility of the females affected by advanced stages of imposex entail a decline in the populations of this gastropod. As it is a species of direct development, the lack of a planktonic phase negatively conditions the recovery of the populations, leading them to extinction in some cases.

Minimum amounts of TBT have been found in whales, dolphins and members of the seal family in the United States, Southeast Asia, the Adriatic Sea and the Black Sea, absorbed through the nutritional chain. In addition, tributyltin reduces the resistance to infections in fish like plaice and other flat fish that live at the bottom of the sea and which are exposed to relatively high levels of TBT, especially in those areas with muddy sediments as is the case of ports and estuaries.

CONSEQUENCES OF VOLATILE ORGANIC COMPOUND (VOC) USE IN ANTIFOULING COATINGS

The only required function of the constituent volatile vehicle of a liquid paint is to allow it to be elaborated and applied. Both the resins or oils, and the solvent free products, form in general solid or semisolid materials that could not be applied by any of the procedures normally used, such as brushes, rollers or pistol.

Generally, the composition of the volatile vehicle in paints responds to a mixture or combination of different solvents. Real resin or fixed vehicles solvents do exist, as do other organic products which, although not fixed vehicle solvent, are used together with the former as paint extenders. The purpose of including these extenders in the formulation of paints, is to improve the application properties and to be able to properly control the evaporation rate of the volatile vehicle during the drying. Their being volatile, the action of solvents is based on their power to dissolve non-volatile organic substances, without either of them experiencing any chemical modification, with the latter being extended in film form after the evaporation has taken place (González, 1994).

The organic chemical agents normally used, like solvents or extenders, belong fundamentally to one of the following types: (Velo, 1996)

— *Petroleum by-products:* aliphatic solvents. Benzine and gasoline are of this type, their being characterised by being insoluble in water, liquid, colourless and with a characteristic smell

— *Soft coal-tar by-products:* aromatic solvents. Benzol and solvent gasoline are of this type, their physical appearance being very similar to that of the petroleum by-products. Chemically, benzol is the aromatic hydrocarbon benzene C_6H_6, while solvent gasoline contains xylene and superior benzene homologs

— *Organic compounds.* Within this group, obtained by means of deferential chemical processes such as the fermentation, distillation, presence of catalysts, alkaline means, etc., are the *Alcohols*, the *Esters*, the *Ethers* and the *Ketones*.

The need to watch the concentrations of VOC fundamentally derives from their own toxicity, since the use of solvents gives rise to emissions of organic compounds in to the atmosphere that can be harmful to health and produce important damage to natural resources. Most volatile organic compounds (VOC) are harmful to ozone and some of them are known cancerigenic agents, which is why it is necessary to reduce their emissions in to the atmosphere. Therefore, the paints being a source of VOC because of solvent evaporation, it has become necessary to consider these compounds as polluting elements when it comes to formulating and manufacturing the paints, no matter what kind they are.

REGULATIONS ON THE MANUFACTURE AND USE OF ANTIFOULING COATINGS

The problems of pollution caused by the TBT present in antifouling paints was dealt with for the first time in the OMI Committee for the Protection of the Marine Environment (CPMM) in 1988, when the Paris 8 Commission asked the OMI to study the need to elaborate measures within the framework of the pertinent legal instruments in order to limit the use of TBT compounds in the seafaring ships. By then there was unequivocal proof on a world-wide scale that tributyltin and other organic by-products of tin compounds were detrimental for aquatic organisms and several countries had already adopted measures either individually or within the framework of regional agreements in order to try to reduce the detrimental effects of antifouling paints containing tributyltin. However, it was clear that it would be necessary to establish international measures to regulate the use of antifouling paints, and in April of 1990, in the Third international symposium on organic by-products of tin compounds, held in Monaco, it was recognised that the OMI was the appropriate organ to carry out that task.

In 1990, in its 30th Sessions, the CPMM adopted the resolution MEPC.46(30) on *"measures to resist the possible adverse effects of the use of tributyltin compounds in antifouling paints"*. In this resolution governments were recommended to adopt measures to eliminate the use of antifouling paints containing compounds of tributyltin in ships of under 25 m in length and whose hull is not of aluminium, and to eliminate the use of antifouling paints whose average rate of leaching is higher than 4 micrograms of tributyltin per cm^2/day.

In 1990, the CPMM of the OMI received the results of a control study of tributyltin, which confirmed the toxicity of tributyltin compounds in marine organisms. The Committee also received information on other existing antifouling systems, which included data on their effectiveness and the risk that they are for the aquatic environment.

In the 38th session, held in 1996, the CPMM established a work group by correspondence so that it could study the pertinent issues. The main conclusions based up on the observations of the 12 countries and four nongovernmental organisations taking part, were presented to the Committee in its 41st session, held in April of 1998.

In the 42nd session, held in November of 1998, the CPMM approved a draft resolution of the Assembly that includes the year 2008 as a deadline for the total prohibition of compounds of organic tin by-products used as byocide in the antifouling systems for ships.

The draft resolution, elaborated by the Work Group that met during the 42nd session of the CPMM, was presented at the 21st Assembly of the OMI, which was held in November of 1999. In this draft resolution the OMI *"urges the Committee for the Protection of the Marine Environment to adopt whatever measures may be necessary to elaborate as quickly as possible a legally binding world-wide scale instrument with the purpose of solving the question of the detrimental effects of the antifouling systems used on ships"*. In addition, the OMI *"decided that the instrument of world-wide character that the Committee for the Marine Environment elaborates would have to guarantee, on a world-wide scale, the prohibition of the application on ships of organic by-products of tin compounds used as byocide in the antifouling systems on ships, by January 1st 2003 at the latest, and the complete prohibition of the presence on ships of organic by-products of tin compounds used as byocide in the antifouling systems, by January 1st 2008 at the latest"*.

As regards VOC, we can make reference to the Royal Decree 117/2003, of January 31st, on the limitation of volatile organic compound emissions due to the use of solvents in certain activities.

The use of solvents in certain activities causes emissions of organic compounds to be released into the atmosphere and which can be injurious to health and produce considerable damage to the natural resources. Bearing in mind the above, the Council of Ministers of the European Union approved, on March 11th 1999, the Directive 1999/13/CE, the aim of which is to prevent or to reduce the harmful effects for people and the environment stemming from those activities that use large quantities of organic solvents in their manufacturing processes or work.

This Directive lays down certain specific regulations for those plants wishing to carry out the above activities, and among which there appear: (i) that of not exceeding the different maximum emission raking for volatile aromatic hydrocarbon emission (hydrocarbons that, under normal conditions of pressure, have a boiling point equal or inferior to 250 °C and which at least have an aromatic ring in its devised structural formula), which will be equal or inferior to 0.5 % of the product; (ii) the one to reduce their emissions by other means, such as using products with a low solvent content or solvent-free. Likewise, the maximum volatile organic compound content (VOC) will be equal or lower to 200 g/l minus the water. The unit used for the VOC content is "mass in grams of COV per litre of product (g/l minus the water).

FUTURE PROPOSALS

From solvents to water

Theoretically it is possible to replace all the solvent-based products that are traditionally on the market whit water-based ones.

Solvent-based paints have: (i) high tolerance in their application and drying under adverse conditions, like, for example, low temperature, discharge humidity; (ii) good behaviour on difficult substrates, such as much deteriorated surfaces; (iii) good application properties; (iv) good mechanical or chemical resistance; (v) good aesthetic appearance. Nevertheless, the technology for water-based is constantly improving.

It's also possible to produce solvent-based products with a lower solvent content by using the modern technology for high solid contents that can be used to formulate products that offer many of the properties attributed to the traditional solvent-based products, but which significantly reduce the solvent content. Although they are more expensive and normally they dry more slowly, they can play an important role in the reduction of emissions. The use of VOC in water-based paint is normally vital for the behaviour of the product and this is particularly true of water-based products that have been formulated to replace the solvent-based ones. Given the present low levels of VOC in water-based products, any reduction that might occur would not be significant to the total amount of the reduction of VOC emissions.

Water-based products are being researched and, together with the high solid content products, are replacing the traditional solvent-based products. It is still possible to achieve even greater reductions in VOC emission by reducing the volatile organic compounds in water-based and solvent-based products and by increasing the use of water-based or high solid content paints. Nevertheless, this will take time. The industry will need to reformulate an important and wide part of its existing product range, and this can only be achieved over a period of several years. What is more, a greater reduction will mean greater changes in products, in application techniques and in the characteristics of its uses. The changes will also have economic consequences originating from the increase in R+D costs and raw materials and will require new investment in equipment.

Review of current research and development activities on antifouling techniques

Environmental concerns about the long-term effects of leach able antifouling biocides have led to increased interest in the development of environmental friendly alternatives. Research activities are centered on biodegradable toxic compounds, non-toxic adhesion inhibitors, electro-chemical systems and cleaning devices.

Natural products: all organisms, benthic and pelagic, must maintain a foul-free surface for their survival. This rationale is largely reflected in the types of organisms that have been investigated for the elucidation of their antifouling mechanisms. Predominantly, the antifouling strategies of sessile organisms have been the subject of several research projects (Clare, 1996; Burgess et al, 2003). The usual approach adopted has been to extract the tissues using solvents and subsequently employ bioassays to assess the antifouling potential of the extracts. The first groups of organisms to be investigated were corals and sponges which were known to maintain a foul-free surface. Tunicates, bryozoa and thallophyta were also thoroughly screened. Red algae extracts have been found to contain halogenated furanones which show biocidal activity comparable to, and sometimes better than that observed with commercial biocides. In more recent investigations crustacea (lobster and shore crabs), echinoderms (sea stars and sea urchins), and the egg-cases of dog-fish were investigated to elucidate their antifouling mechanism as these organisms do not secrete toxic substances to the surface. It was thought that a passive physico-chemical defence system may exist in the egg-cases of dog-fish and in the shell of the shore crab. Egg cases appear remarkably clean, with little or no evidence of macrofouling, even after several months in seawater. Thomason et al. developed the hypothesis that the incorporation of tanning chemicals into the case during its formation by the nidamental gland prevents macrofouling. Other research groups concentrated on the microtexture of egg cases, sea urchin spines and the skin of sea mammals. In general the search for natural compounds is greatly encouraged by the finding that the effect of biogenic antifouling compounds is more based on a repellent mode of action than on a strong toxicity. Thus, research activities are shifting from the detection of toxic molecules to those with little or no toxicity and properties which inhibit microbes and eukaryotic organisms to attach to man-made structures. The search for adhesion inhibitors includes the isolation of active compounds as well as surface properties which inhibit the curing or hardening of the adhesive of fouling organisms (Callow, 2003).

Non-stick coatings: in the last decade several investigations have dealt with non-stick coatings that are mainly based upon silicones and fluoropolymers. About 40 patents have been registered but only a few products are effective and available on the market. The adhesion of settling organisms is remarkably lowered on these coatings. Normally this effect is due to a combination of hydrophobicity, low surface free energy and microroughness. The silicones are composed mostly of polydimethylsiloxanes (PDMS) which may have incorporated exuding silicone oils, paraffin, petroleum wax or fatty acids. The most effective non-stick coatings possess a self-cleaning mechanism, by which the loosely attached organisms are easily removed by turbulence experienced when the vessel is underway, therefore peeling itself off. On the other hand non-stick coatings have their own drawbacks: High price, difficult application, mechanical frailty and persistence. The latter aspect is important with respect to silicone peeling off into the sea and the exudation of silicone oils (Watermann, 1997).

To date, the commercial use of some silicone coatings is expanding from fast naval vessels, patrol boats and fast ferries to cruisers, vehicle carriers and even container ships. Nevertheless the basic mode of action of silicone-based polymers is poorly understood and several research projects are investigating the non-stick properties of silicone polymers. These compounds serve as model substances to develop non-stick surfaces based on natural or degradable polymers.

Electrical devices: for years various ways of using electric currents for the purposes of antifouling have been investigated. Only a select few can presented here however.

The Marine Growth Prevention System by Electrolysis Technology (MAGPET) was developed by Mitsubishi using a conductive type of coating. An electrical current is conducted through the hull causing chloride ions to be transformed into hypochlorite through electrolysis. Hypochlorite is highly toxic to fouling organisms. The advantage of this system over other antifouling systems is to activate the system only when necessary, i.e. in harbours or in service at low speed. In total, the energy demand is said to be very low ranging in roughly 0.2 W/m^2. A drawback to this system is that even though hypochlorite decomposes rapidly in water, halogenated by-products are created by the electrolytic action. The creation of halogenated by-products has been documented in both drinking water treatments and chlorinated cooling systems.

Another direction to use electrical currents is based on the principle that the pH value is discontinuously changed on a specific prepared surface. Driven by a periodical electrical drive the conductive outer coating induces changes in the pH-value at the surface for several hours thus preventing the attachment of fouling organisms. Successful laboratory and field trials on panels have been conducted in the last years. Field trials with test patches on ship hulls and fully treated ships are ongoing. Special attention must be paid to maintenance, repair, and functionality at focal damage.

Control of fouling by cleaning: underwater cleaning has been practiced for many years, but has never been more than a "fill in" activity, used as an expedient to bridge the gap between the exhaustion of the coating and the next dry-docking. Several companies offer a world-wide hull cleaning service. Cleaning is mostly carried out on moored ships or in harbours during loading and unloading by divers using an impeller system with rotating brushes. These cleaning actions have become more restricted because the resulting acceleration of biocide release from the paint causes high levels of pollution. As the cleaning companies are aware of the declining business on biocidal antifouling paints, some of them have since developed a non-toxic hull concept. The idea was to coat the hull with a really hard, smooth anticorrosive system and to maintain it in this condition by regular underwater cleaning over several years. Investigations on the fouling growth arising between cleaning intervals revealed that special coatings are necessary to extend cleaning intervals up to several months.

Fouling development is essentially influenced by the type of service of the ship. Fast ferries with short times in harbours or cruise liners have fewer problems compared to very large, crude oil carriers (VLCC) or carriers which are sometimes moored for several weeks.

More sophisticated systems such as robots are needed to have flexible technique and to allow cleaning to be carried out on demand. A network of hull cleaning stations on all the important trade routes would be necessary with the cleaning entirely automated, either by means of a remote controlled vehicle or along lines of a car wash system. Difficult areas such as bilge keels, rudder and stern arch would still need to be cleaned by divers or coated by non-stick coatings as silicones. Initiatives to modify swim-docks as floating cleaning stations for large ships are published but not yet realised.

REFERENCES

Burgess J. G., Boyd K., Armstrong E., Jiang Z., Yan L., Berggren M., May U., Pisacane T., Granmo A., Adams D.; (2003): *The development of a marine natural product-based antifouling paints.* Biofouling 19 (supplement), pp. 197-205.

Callow M.; (2003): Some new insights into marine biofouling. World Super Yacht, 1, pp.34-39.

Clare A. S. (1996): *Marine natural product antifoulants: status and potential.* Biofouling 9, pp. 211–229.

Eguía E. et al (1996): *Biofouling Marino: Fenómeno Biológico Estrechamente Relacionado con el Buque y el Puerto.* II Jornadas de Estudios Portuarios y Marítimos. Bilbao. Asociación de Estudios Portuarios y Marítimos.

García Pastor B.J. (1996): *Estudio del Crecimiento del Biofouling sobre Estructuras Artificiales en la Bahía de Santander.* Tesis Doctoral. Dpto. Ciencias y Técnicas de la Navegación y de la Construcción Naval. Universidad de Cantabria.

González J. (1994): *La Pintura como Recubrimiento Protector.* Ed. A. Madrid Vicente. 1ª Ed. Universidad Politécnica de Madrid, pp. 7-229.

Jelic-Mrcelic G., M. Sliskovic and B. Antolic (2006): Biofouling communities on test panels coated with TBT and TBT-free copper based antifouling paints. Biofouling 22, (5), pp. 293-302.

Organización Marítima Internacional (1999): *Sistemas antiincrustantes.* La OMI al día

Quintela, M. (2002): *Cambio de sexo en moluscos gallegos.* Universidad de la Coruña.

Velo M.; (1996): *Conceptos Básicos de la Tecnología de las Pinturas.* Ferroluz, pp. 1-16.

Watermann B., H.-D. Berger, H. Sönnichsen and P. Willemsen (1997): Performance and effectiveness of non-stick coatings in seawater. Biofouling, 11,(2), pp.101-118.

Yebra D. M., S. Kiil and K. Dam-Johansen (2004): Antifouling technology - past, present and future steps towards efficient and environmentally friendly antifouling coatings. Progress in Organic Coatings 50, (2), pp.75-104.

ESTUDIOS RECIENTES EN SISTEMAS ANTIFOULING APLICADOS A ESTRUCTURAS ARTIFICIALES EN AMBIENTES MARINOS

RESUMEN

Las estructuras artificiales en contacto con el agua de mar, se ven sometidas rápidamente al recubrimiento de una biopelícula microbiológica, la cual sirve como base para el crecimiento de los macro-organismos. Esto se conoce como el fenómeno del biofouling, así bien, la consecuencia negativa que esto provoca para las estructuras artificiales en contacto con el agua de mar, es en forma de defectos estructurales y sobre todo el gasto adicional que supone para las compañías, las cuales desarrollan sus trabajos en el ámbito marino, debiendo aplicar procesos de limpieza y prevención para su eliminación. La evolución en la tecnología entorno a las pinturas antifouling, una vez que hemos analizado los problemas causados por el uso indiscriminado de biocidas con un alto grado de toxicidad en su composición, así como las derivaciones orgánicas en la formación de los componentes del estaño, las emisiones incontroladas de los componentes orgánicos volátiles (COV) a la atmósfera, y de acuerdo a las leyes ambientales actuales, se tiene como única alternativa el desarrollar recubrimientos medioambientalmente inocuos en base agua, en los que se utilicen como compuestos biocidas extractos del propio medio marino.

Palabras clave: Biofouling, pinturas antiincrustantes, compuestos organoestánnicos, compuestos orgánicos volátiles (COVs), normativa medioambiental.

INTRODUCCIÓN

Toda estructura artificial en contacto con agua de mar es rápidamente cubierta por una biopelícula microbiológica que sirve como base de asentamiento de macroorganismos. Este fenómeno, conocido como biofouling, causa problemas estructurales graves y su mitigación acarrea un severo gravamen económico para las industrias que operan en el medio marino.

Son cientos las especies que pueden formar parte del biofouling, fijándose al sustrato desarrollando un rápido crecimiento y gran potencial reproductor. Como consecuencia, el biofouling acelera los procesos de corrosión de los materiales y provoca pérdidas en la eficacia operativa de las estructuras en contacto con agua de mar. En las embarcaciones se incrementa la fricción entre el casco y el agua lo que comporta un aumento del consumo de combustible y la pérdida de velocidad y capacidad de maniobra.

Para evitar las pérdidas económicas, así como un deterioro acelerado de las estructuras artificiales en contacto con agua de mar, vienen empleándose distintos tipos de protecciones desde antiguo. Entre ellas destacan los revestimientos de cobre que comenzaron a ser utilizados por los fenicios y que siguieron empleándose con éxito hasta el siglo XVIII sobre embarcaciones de madera. Con la aparición de los buques de hierro comenzaron a elaborarse pinturas en las que el sulfato de cobre actuaba como principio biocida. A partir de 1960 se extendió el uso de pinturas en cuya composición podíamos encontrar cobre, mercurio, arsénico, derivados organoestánnicos (compuestos orgánicos del estaño como el tributilestaño (TBT) y la trifeniltina (TPT)), las cuales con el paso del tiempo, se ha podido comprobar que suponían un riesgo real para el ecosistema marino.

En la década de los setenta se extendió el empleo de recubrimientos antiincrustantes basados en la actuación biocida de los derivados organoestánnicos, en especial del tributilestaño (TBT), por lo que la mayoría de los buques de navegación marítima recubrieron sus cascos con este tipo de pinturas, que resultaron ser eficaces y económicas.

Durante la década de los ochenta se tomó conciencia de las consecuencias que el uso del TBT en las pinturas antiincrustantes estaba teniendo sobre los ecosistemas marinos, especialmente en áreas de bajo intercambio de agua por influencia mareal, como bahías o estuarios, donde resulta especialmente perjudicial sobre las poblaciones de algunos invertebrados, moluscos, crustáceos y peces, detectándose malformaciones muy importantes en algunas especies. Como consecuencia de la preocupación desatada ante estos hechos, varios países introdujeron controles para limitar el uso de TBT en las pinturas antiincrustantes en los buques pequeños. Así, en 1982, Francia prohibió el uso de TBT en los buques con una eslora inferior a 25 m, siguiendo su ejemplo Japón, Reino Unido, Estados Unidos, Noruega, Australia, Nueva Zelanda y otros países.

A principios de los años noventa, una resolución de la OMI recomienda a los gobiernos la prohibición del uso de tributilestaño en los buques de eslora inferior a 25 m y se imponen restricciones en el proceso de lixiviación del tributilestaño, debiendo de ser inferior a 4 microgramos por cm^2 /día. Países como Japón, Nueva Zelandia y Australia prohiben el uso de antiincrustantes que contengan TBT (OMI, 1999).

En 1997, Japón prohibe la fabricación de pinturas antiincrustantes que contengan TBT, siendo el 1 de enero de 2003 la fecha propuesta para la prohibición del uso de compuestos organoestánnicos como biocidas en los sistemas antiincrustantes, quedando para el año 2008 su total prohibición.

CONSECUENCIAS DEL USO DE COMPUESTOS ORGANOESTÁNNICOS COMO BIOCIDAS EN LAS PINTURAS ANTIINCRUSTANTES

En general todos los compuestos orgánicos del estaño, y en particular el tributilestaño (TBT), son compuestos extremadamente tóxicos, incluso a concentraciones de pocos nanogramos por litro. La magnitud de los efectos del TBT y la repercusión sobre la legislación de su uso fueron particularmente destacables en las ostras y los neogasterópodos, aunque también se han encontrado cantidades mínimas de TBT en ballenas, delfines y miembros de la familia de las focas en los Estados Unidos, sudeste asiático, Mar Adriático y Mar Negro, absorbido a través de la cadena alimenticia. Además, el tributilestaño reduce la resistencia a las infecciones en peces como la platija y otros peces planos que habitan en el fondo del mar y que están expuestos a niveles relativamente altos de TBT, en particular en las zonas con sedimentos limosos como es el caso de puertos y estuarios.

CONSECUENCIAS DEL USO DE COMPUESTOS ORGÁNICOS VOLÁTILES (COVS) EN LAS PINTURAS ANTIINCRUSTANTES

El vehículo volátil constituyente de una pintura líquida, tiene como única misión permitir su elaboración y aplicación. Tanto las resinas o aceites, como los productos exentos de disolvente, forman en general materiales sólidos o semisólidos que no podrían ser aplicados por cualquiera de los procedimientos normalmente utilizados, tales como brocha, rodillo o pistola.

La necesidad de vigilar las concentraciones de COVs se deriva fundamentalmente de su propia toxicidad, ya que el uso de disolventes da lugar a emisiones de compuestos orgánicos a la atmósfera que pueden ser nocivas para la salud y producir importantes perjuicios a los recursos naturales. La mayoría de los compuestos orgánicos volátiles (COVs) son precursores del ozono y algunos de ellos son conocidos agentes cancerígenos, por lo que es necesario disminuir sus emisiones a la atmósfera. Por lo tanto, siendo las pinturas una fuente de COVs por evaporación de disolventes, se hace necesario considerar como elemento contaminante estos compuestos a la hora de formular y fabricar las pinturas, sean de la naturaleza que sean.

NORMATIVA RELATIVA A LA FABRICACIÓN Y USO DE PINTURAS ANTIINCRUSTANTES

Los problemas de contaminación causados por el TBT presente en las pinturas antiincrustantes se trató por primera vez en el Comité de Protección del Medio Marino (CPMM) de la OMI en 1988, cuando la Comisión de París 8 solicitó a la OMI que estudiase la necesidad de elaborar medidas en el marco de los instrumentos jurídicos pertinentes para limitar el uso de los compuestos de TBT en los buques de navegación marítima.

En 1990, en su 30° periodo de sesiones, el CPMM adoptó la resolución MEPC.46(30) sobre *"medidas para contrarrestar los posibles efectos adversos del empleo de compuestos de tributilestaño en las pinturas antiincrustantes"*. En dicha resolución se recomienda a los gobiernos que adopten medidas para eliminar el empleo de pinturas antiincrustantes que contengan compuestos de tributilestaño en los buques de eslora inferior a 25 m. y cuyo casco no sea de aluminio, y eliminar el empleo de pinturas antiincrustantes cuya tasa media de lixiviación sea superior a 4 microgramos de tributilestaño por cm^2 /día.

El proyecto de resolución, elaborado por el Grupo de trabajo que se reunió durante el 42º periodo de sesiones del CPMM, se presentará a la vigésima primera Asamblea de la OMI, que se celebrará en noviembre de 1999. En dicho proyecto de resolución la OMI "insta al Comité de Protección del Medio Marino a que adopte las medidas necesarias para elaborar de forma rápida un instrumento jurídicamente vinculante a escala mundial con el fin de resolver la cuestión de los efectos perjudiciales de los sistemas antiincrustantes utilizados en los buques". Además la OMI "decide que el instrumento de carácter mundial que elabore el Comité de Protección del Medio Marino debería garantizar la prohibición a escala mundial de la aplicación en los buques de compuestos organoestánnicos utilizados como biocidas en los sistemas antiincrustantes en los buques, el 1 de enero de 2003 a más tardar, y la prohibición completa de la presencia en los buques de compuestos organoestánnicos utilizados como biocidas en los sistemas antiincrustantes, el 1 de enero de 2008 a más tardar".

En cuanto a los COVs podemos hacer referencia al Real Decreto 117/2003, de 31 de enero, sobre limitación de emisiones de compuestos orgánicos volátiles debidas al uso de disolventes en determinadas actividades.

PROPUESTAS DE FUTURO

Del disolvente al agua

Teóricamente es posible sustituir todos los productos que tradicionalmente están en el mercado de base disolvente por versiones en base agua.

También es posible producir productos de base disolvente con un menor contenido de disolvente utilizando la moderna tecnología de altos contenidos en sólidos que puede ser usada para formular productos que ofrecen muchas de las propiedades que se atribuyen a los tradicionales productos en base disolvente, pero que reducen significativamente el contenido de disolvente.

Alternativas a los compuestos organoestánnicos

Los sistemas antiincrustantes que no contienen TBT pueden estar compuestos por matrices solubles de agua marina que contienen ingredientes libres de estaño biológicamente activos. Los biocidas se dispersan y quedan contenidos en la matriz, aunque no estén necesariamente ligados a ella mediante un enlace químico. En la interfaz agua marina/pintura, el biocida se lixivia a un ritmo controlado. La matriz se disuelve y libera nuevo biocida, lo que permite lograr un rendimiento predecible.

Las principales opciones de que se dispone en la actualidad son las siguientes:
— Pinturas antiincrustantes a base de cobre.
— Pinturas antiincrustantes libres de estaño.
— Revestimientos antiadherentes.
— Limpieza.
— Electricidad.
— Revestimientos con púas.
— Resistencia natural, biocidas naturales.

En la actualidad, estamos ensayando la eficacia como biocidas en pinturas antiincrustantes de diferentes compuestos naturales extraídos del propio medio marino, en una investigación financiada por el Ministerio de Ciencia y Tecnología de España a través del Proyecto REN-0519/TECNO titulado *«Aplicación de biotecnología marina en la producción de recubrimientos antiincrustantes medioambientalmente inocuos»,* en el que participa el Departamento de Ciencias y Técnicas de la Navegación y de la Construcción Naval de la Universidad de Cantabria y colaboran la Autoridad Portuaria de Santander, la empresa cántabra de pinturas Ferroluz S.A., el laboratorio escocés Ecosearch (International) Ltd. y el Departamento de Ciencias Biológicas de la Universidad de Heriot-Watt.

INSTRUCTIONS FOR AUTHORS

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The objective of JMR is to contribute to the progress, development and diffusion of research on the maritime sector. The aim is to provide a multidisciplinary forum for studies of the sector from the perspective of all four of the following broad areas of scientific knowledge: experimental sciences, nautical sciences, engineering and social sciences.

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- ☐ Size: DIN A4 (29 cm by 21 cm)
- ☐ Margins, 3 cm: top, bottom, left, and right.
- ☐ Font: Times New Roman, normal style, 12-point type.
- ☐ Double spacing should be used for all the paper except for the references which are to be single-spaced.
- ☐ Notes, when necessary, are to be placed at the end of the paper and numbered in their order of appearance in the text. Mathematical derivations should not be included in these endnotes.

The abstract is to be presented on one page and should include the following information:

- ☐ Title and subtitle of the paper
- ☐ Field and sub-field of the work presented.
- ☐ Abstract, which is to be no longer than 200 words, and should have no spaces between paragraphs.

- ☐ Key words (between 3 and 5) which will be used for computerised indexing of the work, in both Spanish and English.
- ☐ The complete work should be no longer than 23 pages (about 7000 words) and should be structured as is shown below.

The first page will contain the same information as the summary:

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The rest of the article:

- ☐ Introduction or Problem
- ☐ Methods
- ☐ Development (application and results)
- ☐ Conclusions
- ☐ Endnotes
- ☐ References. Only those included in the article in alphabetical order.
- ☐ Appendix containing a condensed version of the article in Spanish. This is to be 3 or at most 4 pages in length (approximately 1000-1200 words) with the following sections: abstract, methods and conclusions.

The body of the article is to be divided into sections (bold, upper-case), subsections (bold, italics) and optionally into sub-subsections (italics), none of which are to be numbered. Insert line spaces before and after the title of each section, subsection and sub-subsection. Symbols, units and other nomenclature should be in accordance with international standards.

References

The Harvard System is to be used, following the guidelines indicated below.

The way in which *bibliographic citations* are included in the text will depend on the context and the composition of the paragraph and will have one of the following forms:

- ☐ One author: Farthing (1987); (Farthing, 1987); (Farthing, 1987 pp. 182-5)
- ☐ Several authors: Goodwin and Kemp (1979); Ihere, Gorton y Sandevar (1984); Ihere et al.(1984); (Ihere et al., 1984)

The *bibliographic references* are to be arranged in alphabetical order (and chronologically in the case of several works by the same author), as is indicated in the following examples:

Books

Farthing, B. (1987) *International Shipping.* London: Lloyd´s of London Press Ltd.

Chapters of books

Bantz, C.R. (1995): Social dimensions of software development. In: Anderson, J.A. ed. *Annual review of software management and development*. Newbury Park, CA: Sage, 502-510.

Journal articles

Srivastava, S. K. and Ganapathy, C. (1997) Experimental investigations on loop-manoeuvre of underwater towed cable-array system. *Ocean Engineering* 25 (1), 85-102.

Conference papers and communications

Kroneberg, A. (1999) Preparing for the future by the use of scenarios: innovation shortsea shipping, *Proceedings of the 1st International Congress on Maritime Technological Innovations and Research,* 21-23 April, Barcelona, Spain, pp. 745-754.

Technical Reports

American Trucking Association (2000) *Motor Carrier Annual Report*. Alexandria, VA.

Doctoral theses

Aguter, A. (1995) *The linguistic significance of current British slang*. Thesis (PhD).Edinburgh University.

Patents

Philip Morris Inc., (1981). *Optical perforating apparatus and system*. European patent application 0021165 A1. 1981-01-07.

Web pages and electronic books

Holland, M. (2003). *Guide to citing Internet sources* [online]. Poole,
Bournemouth University. Available from:
http://www.bournemouth.ac.uk/library/using/guide_to_citing_internet_sourc.html
[Accessed 1 November 2003]

Electronic journals

Storchmann, K.H. (2001) The impact of fuel taxes on public transport — an empirical assessment for Germany. *Transport Policy* [online], 8 (1), pp. 19-28 . Available from:
http://www.sciencedirect.com/science/journal/0967070X
[Accessed 3 November 2003]

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Equations are to be written with the Microsoft Word Equation Editor using right-justified alignment. They should be numbered consecutively using Arabic numerals within parentheses.

Tables should be inserted in the appropriate point in the text using Microsoft Word. They should be numbered consecutively with Arabic numerals and a concise title should be centred at the top of the table. The source is to be indicated at the bottom on the left. Any symbols used should be explained.

Illustrations are to be inserted in the appropriate point in the text using Microsoft Word. All illustrations (graphs, diagrams, sketches, photographs, etc.) will be denominated generically Figures and are to be numbered consecutively using Arabic numerals with the title centred at the top. The source is to be indicated at the bottom on the left. Photographs must be in black and white with a quality of at least 300 ppp.