GOAL-BASED SHIP SUBDIVISION AND LAYOUT

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ABSTRACT

Tradition is no longer adequate to cope with the rapidly changing innovation in passenger ships, nor is it possible to deal with the drastic increase in societal expectation on the accepted level of risk. The new probabilistic regulations for damage stability that came into force in January 2009 is a sign that the shipping industry in general has made a shift in the way of thinking but even this is scratching the tip of the amounting need to rethink, reformulate and resolve how to curtail safety and environmental problems and to enhance both cost-effectively. New methods have to be deployed, using knowledge in all forms, rather than having to wait for major accidents to happen to enrich current statistics and henceforth take action. These methods should be able to quickly evaluate different designs in all aspects of their performance. Goal-Based Design, as opposed to Risk-Based Design, suggests that the design focus is on balancing all pertinent goals rather than focusing on risk reduction and mitigation alone. In this process, safety would still have to be accounted for as a design objective so that it can be dealt with in an early stage in the design process when it is mostly inexpensive but performance and life-cycle issues must be an integral part of any decision making.

KEYWORDS: *Goal-Based ship design, SOLAS '09, survivability formulation, probabilistic regulations, subdivision, layout*

1. INTRODUCTION

Ship subdivision and layout are two of the most important issues affecting ship performance, functionality and safety, all of which have to date been catered for through the provision of rules and regulations that reflect, in essence, codification of best practical experience. Changing the regulations and leaving on the table a blank sheet, makes ship subdivision a very difficult problem indeed. However, building on the understanding of probabilistic damage stability, affords a straightforward way of determining the relative collision and flooding risk profile of a vessel at an early design stage and hence devising an effective means of risk reduction by focusing primarily on the high risk scenarios contributing to the said risk. The fully automated optimisation process typically produces several hundred design alternatives depending on the complexity of the ship's layout and the number of variables utilised. Typical variables of the optimisation problem include: type of subdivision, number, location and height of watertight bulkheads, deck heights, tank arrangement, casings, double hull, and position of staircases, lifts and escape routes. Using the Attained Subdivision Index, payload, steel weight and other regulatory requirements as typical objectives, the optimisation problem outcome typically includes: definition of number of bulkheads and deck heights, reduction of void volumes, definition of escape routes and required staircases, reduced steel weight, simplicity of tank arrangement, increased crew and service areas, improved functionality and enhanced safety. In order to make the process effective, participation by all decision-makers (designer, owner and yard) is essential to properly define the optimisation variables, objectives and constraints as early as possible in the design stage. Using this approach, known as platform optimisation, high survivability internal ship layouts have been developed, without deviating much from the current SOLAS practice, thus making it easier for ship designers to relate to the proposed procedure. In the process of applying the aforementioned procedure to a number of new building designs, a number of issues have surfaced in need of improvement in order to maximize the benefit that can be derived from contemporary developments in ship safety. Deriving from the above, this paper aims to address the specific (but extremely important) area of ship subdivision and layout by adopting a Goal-Based Design framework and by developing and implementing suitable models and tools to aid ship design in the concept stage. A specific case study is used to clarify the ideas presented.

2. DEFINITION OF GOAL-BASED DESIGN

Conning the term Goal-Based Design might appear to be rather superfluous as the design process is by definition goal-based but in this context it is meant to represent a generic term used for a more general application than Risk-Based Design in that the design focus is on balancing all pertinent goals (targeting performance, functionality and safety/risk) rather than focusing on risk reduction and mitigation alone. The difficulty encountered by the naval architect even in an early stage of the design process can be simply demonstrated by the following figure:

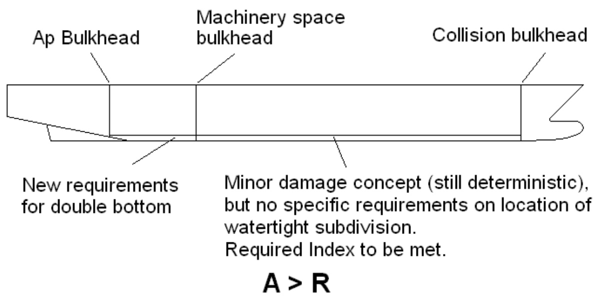

Figure 1. Difficulty of the design process.

In order to simplify the process, the different goals to be addressed need to be itemised. Some examples include:

- Damage stability – e.g., minimum 3 hours survival time, for Safe Return to Port related requirements.
- Operation – e.g., critical systems availability at all times, maximum people and goods flows
- Cost / earnings – e.g., minimum building cost, minimum life-cycle operating costs
- Fire safety – e.g., ASET>RESET in all critical fire scenarios

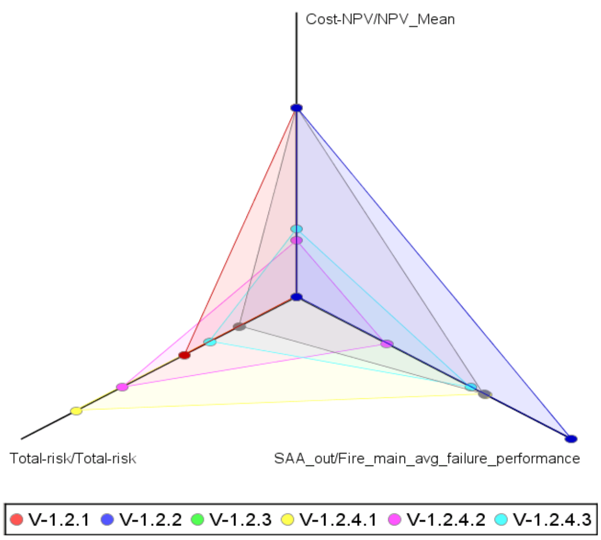

Figure 2. Pictorial Representation of Goal-Based Design.

Only when all of the above issues have been addressed concurrently (Figure 2) can it be claimed that an optimum design has been achieved. To this end and to be able to quantify these goals, pertinent criteria have to be set as outlined in the following.

3. METHODOLOGY

This work in this paper is based on a NAPA database of a currently existing cruise ship. More specifically, the hull of the model was used as a base upon which a parametric model was created. The main dimensions of the ship and a drawing of its hull are shown in Table 1 and Figure 3 below.

Table 1. Main dimensions of the model ship.

L_{OA} =	318.41	m
L_{BP} =	293.7	m
T_{DWL} =	8.3	m
T_{MAX} =	8.6	m
B_{MAX} =	36.8	m
B_{REF} =	36.8	m
H_{MD} =	11.3	m
H_{MAX} =	60	m
C_B =	0.6362	
Displacement =	58,751.2	mt
N_{PA} =	3148	

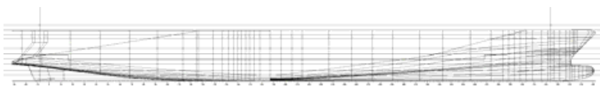

Figure 3. Hull of the base model.

A NAPA macro was written to produce the subdivision elements such as bulkheads and decks as well as the room definitions and functions. The parameters were separated in two groups: watertight subdivision below the bulkhead deck and watertight subdivision above it. These, of course, could be considered concurrently but this approach helps to demonstrate the fact that subdivision must now be addressed as a whole ship problem not just of the ship hull!

3.1 Watertight subdivision below the bulkhead deck

The optimum number of bulkheads is probably the first major issue that the designer encounters when first dealing with the subdivision of the ship. Its value has a large impact on the survivability of the ship but can also increase building cost and manufacturing complexity. SOLAS regulations were catering for this up to now by providing criteria like the minimum and maximum compartment length, the margin line and subdivision index which predefined the number and position of bulkheads. Without these values a target has to be set to aim for. Previous work done towards this direction demonstrated that an optimum number of bulkheads can easily be found, as survivability – measured in terms of Index A – reaches a stagnation point. (Tsakalakis, 2007). Figure 4 below shows the value Index A attains as number of bulkheads increases, as well as the stagnation point and optimum number of bulkheads. This can also be the way to estimate the initial number of bulkheads to use in starting the design loop. Using main openings and basic tanks arrangements could complicate the process further but as experience is gained, the task becomes progressively easier to handle.

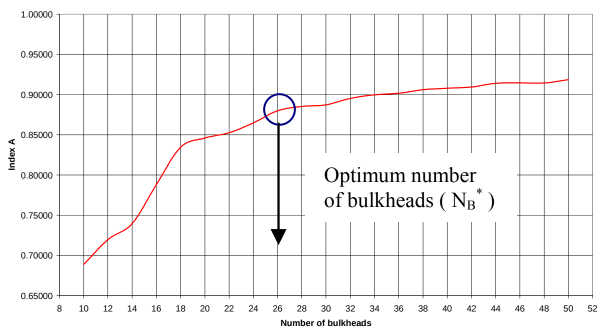

Figure 4. Index A – # BHDs.

According to SOLAS 2009 the required Index (R) for this ship is just below 0.8, so the number of bulkheads that would be used for this case study was chosen to render Index A meet this basic requirement. The results obtained suggest three different values, 17, 18 and 19 all being representative numbers for a vessel of this size. The macro used for the generation of the different configurations can also give number, size and position of tanks, heeling tanks and several stores as well as double side shell. However, in this study all these quantities were kept unaltered for all design alternatives. A sample configuration is shown in Figure 5

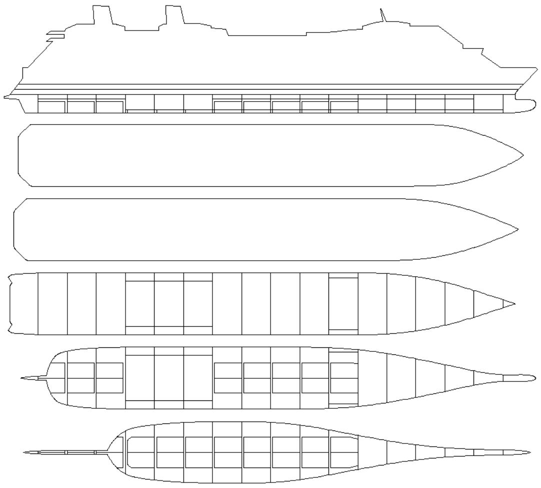

Figure 5. Sample design alternative.

3.2 Watertight subdivision above the bulkhead deck.

It is a known fact that watertight subdivision above the main deck can aid significantly to the survivability of a ship. However, introducing watertight subdivision above the main deck can downgrade the ships functionnality by increasing travelling times for passengers and crew and hindering flow of goods and services. This is the reason why any sort of subdivision here has to be minimal and optimised. Two main alternative designs were considered here, one with a narrow corridor between two towers of cabins and another with a wider corridor. There are no watertight barriers in the corridor, thus making functionality better but the accommodation spaces are subdivided by watertight bulkheads. Two variations of this design were used, one being denser subdivided than the other. An example of a design alternative featuring watertight subdivision above the main deck is shown in Figure 6.

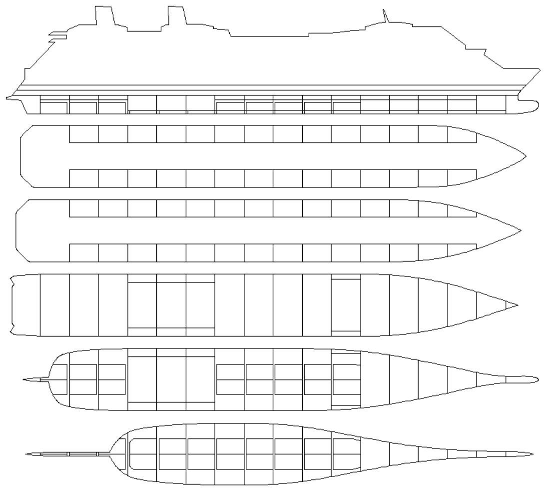

Figure 6. Sample design alternative.

These parameters were used to create 27 different arrangements the performance of which is measured against set criteria as outlined next.

4. DEFINITION OF CRITERIA

To illustrate the concept, three, rather arbitrary, criteria used in this case study for evaluating the performance of each design variant: damage survivability, operational functionality and cost. The performance of a design with regards to cost can be measured with use of detailed cost modules or simpler criteria such as steel weight. Operational issues related, for example, to power and speed, are more straightforward to conceive. These tree issues are being considered, in turn, in the following.

4.1 Survivability

The real challenge in setting design criteria starts with the complex problem of safety. This was usually dealt with by rules and regulations and not by addressing it as a design objective right from the beginning of the design process. Previous safety regulations contributed to this perception by being mostly prescriptive. The new probabilistic regulations and specifically the Attained Subdivision Index have complicated matters considerably, particularly because of lack of experience in designing with modern tools and to some extent lack of trust in their usefulness. However, the new regulations give the designer increased flexibility, provided they can be addressed systematically. Whatever the issues, Index A has the potential to be an excellent overall performance criterion with regards to collision ∩ flooding survivability. By saying ‘potential’ it is implied that reference needs to be made to inherent problems in its formulation in need of attention (Vassalos, 2007). Notwithstanding this, the new probabilistic damage calculations (Index A) of SOLAS 2009 (MSC.216(82) – Annex 2) is used for measuring the survivability of each design variant.

Current formulation

The basis of the survivability formulation of the new harmonized probabilistic regulations is the following:

$$s_i \approx K \cdot \left[\frac{GZ_{max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}} \qquad (1)$$

where:

GZ_{max} is not to be taken as more than 0.12 m;

Range is not to be taken as more than 16 degrees;

K= 1 if $\theta_e \leq \theta_{min}$

K= 0 if $\theta_e \geq \theta_{max}$

$K = \sqrt{\dfrac{\theta_{max} - \theta_e}{\theta_{max} - \theta_{min}}}$ otherwise;

“θ_{min}” is 7 degrees for passenger ships and 25 degrees for cargo ships, and

“θ_{max}” is 15 degrees for passenger ships and 30 degrees for cargo ships.

The problem lies within the ‘harmonised’ concept. The above formula (1) is adequate when it refers to conventional ships to which the limits apply rather well. However, when it comes to different types of ships these limits should be changed accordingly. What are the correct limits presently? The same results that were used to quantify the existing limits could provide the solution. A significant number of experiments were carried out during the project HARDER. There was no significant difference between conventional ships and Ro-Pax with regards to the correlation between maximum range and survivability, but this is not the case concerning maximum GZ as can be seen in Figure 7.

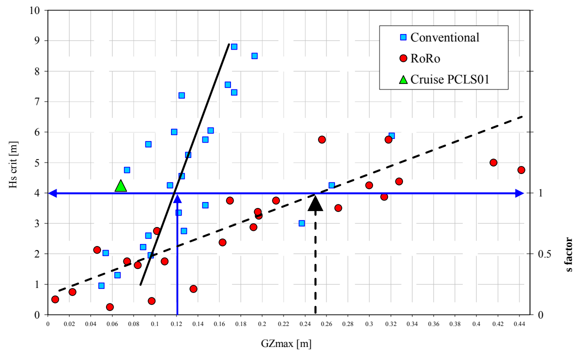

Figure 7. GZ_{max} data for Ro-Ro passenger ships and conventional ships.

GZ_{max} was chosen not to be greater than 0.12 m because this is approximately the point at which the trend line (continuous line) formed by the scattered experimental points for conventional ships (square points) crosses the 4 m significant wave height which, by statistical knowledge, is the highest possible wave height (with a 0.99 probability) that can occur during a collision incident. However, these points are only relevant to conventional ships. It is rather clear that points derived from survivability experiments for Ro-Pax (round points) demonstrate a completely different trend. As indicated in Figure 7, the trend line for Ro-Pax (dashed line) crosses 4 m Hs close to 0.25 m GZ_{max}. This suggests that formula 1 should be revised for Ro-Pax to account for this rather large difference. The argument that such difference is compensated by same trend lines concerning GZ Range is a rather thin one, for two reasons: (a) GZ_{max} is a dominant parameter when the problem relates to water on deck for Ro-Pax ships and (b), an unrepresentative relationship linking design to environmental parameters will misguide and confuse designers.

At this point it would be worth mentioning that formula 1 is also applied to cruise ships, for which t almost no data were available at the time the aforementioned formulation was derived. The one point in Figure 7 that is a cruise ship is clearly not enough to derive conclusions. Furthermore, based on recent extensive tests on a cruise ship model, it has become clear that the current formulation underestimates the survivability of cruise ships, the flooding of which is a very complicated process as is their internal arrangement. Figure 8 below (derived at scenario level) demonstrates large differences between results of the analytical solution (according to SOLAS 2009) and those derived from simulations and physical model tests.

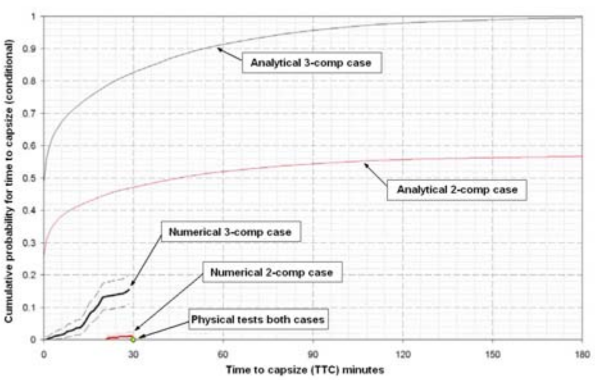

Figure 8. Comparison of analytical, numerical and experimental data for a large cruise ship.

There is a difference of an order of magnitude between predictions for survivability by the analytical model and those of the numerical simulations and experimental tests. Thus, it is apparent that there is a need to define a more representative formulation for index of survivability, maybe one for each type of ship as outlined next.

<u>Proposed formulation</u>

As a result of the above, a study has been undertaken to find a better suiting formula for each type of ship. Due to already existing data (HARDER project) for Ro-Pax ships albeit was possible to alter formula 1 to suit this type of ship. The resulting formula is:

$$s_i \approx K \cdot \left[\frac{GZ_{\max}}{0.25} \cdot \frac{Range}{16} \right]^{\frac{1}{2}} \qquad (2)$$

Where:

GZ_{max} is not to be taken greater than 0.25m and the rest as per formula 1.

It will be noted that the only change relates to GZ_{max} as the Range values were quite similar between conventional and Ro_pax ships. Using this particular formula for a number of Ro-Pax ship databases available internally it was possible to derive an estimate of the difference these two formulae. Figure 9 below is an example of one of these.

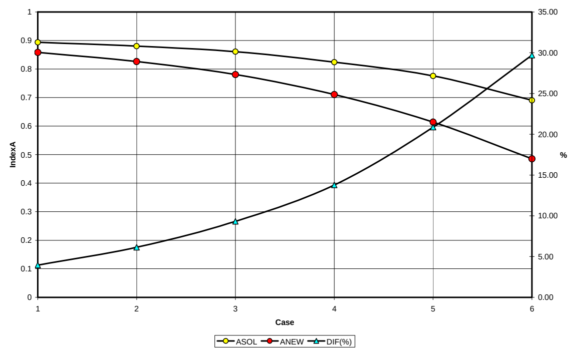

Figure 9. Survivability difference between current and proposed formula.

The cases shown correspond to altered GM values of the same ship, which leads to reduced survivability. In all cases the prediction of formula 2 is lower than that of the first and as can be seen from Figure 9 the difference becomes bigger as survivability of the ship decreases! This is because the number of cases giving s=1 that are not actually affected by the change in formulation decreases as survivability of the ship decreases. The value 0.25 for GZ_{max} could also be verified by regression analysis on the results from project HARDER. What we had from that project was GZ_{max}, Range and survival Hs for 25 Ro-Pax ships. Using the statistically derived correlation of Hs and s which is:

$Hs_{crit}(s) = Hs_{collision}(s) \Rightarrow$ $Hs_{crit,i} = \dfrac{0.16 - \ln(-\ln(s_i))}{1.2} \Rightarrow$ $s_i = \exp(-\exp(0.16 - 1.2 \cdot Hs_{crit,i})$	(3)
$s_i = \left(\dfrac{GZ_{\max,i}}{GZ_{\max}} \cdot \dfrac{Range_i}{16} \right)^{\frac{1}{2}} \Rightarrow$ $GZ_{\max} = GZ_{\max,i} \cdot \dfrac{Range_i}{16} \cdot \dfrac{1}{s_i^{\,2}},$ $i = 1 - 25$	(4)

Solving formula 3 we were able to get s values for each ship and then solve the formula 4 for each one with the only unknown being GZ_{max}. This gave an average value of 0.2525 (Figure 10) which was rounded to 0.25 for simplicity.

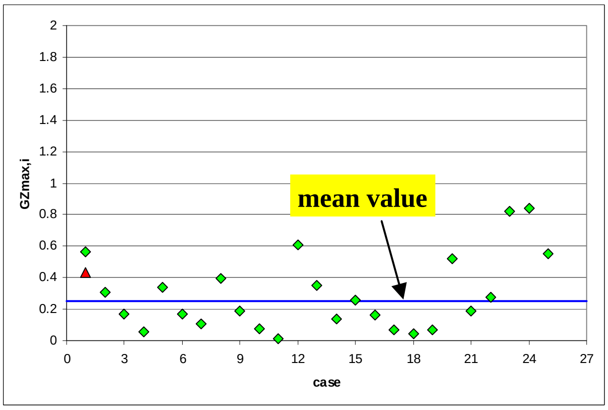

Figure 10. Values of GZ_{max} for each ship and mean value.

The same procedure is currently being utlised to derive a suitable formulation for cruise ships and will be reported in a future publication.

4.2 Functionality

The ratio between watertight spaces and overall volume of the ship was used as a measure of ship functionality. This is a simplistic approach according to which the more tightly a ship is subdivided the more complex it becomes; hence its functionality is being lowered.. NAPA's tables were extracted to measure the average compartment volume, which was then divided by the total volume of the ship to give an index of compartmentation that can be summarised in the expression shown below:

$I_V = \dfrac{v_i / n_i}{V_{TOTAL}}$	(5)

Where:

n_i is the number of compartments
v_i is the volume of each compartment and
V_{TOTAL} is the total volume of the ship up to the height modelled (2 decks above main deck)

4.3 Cost

A simple cost model was used since the purpose of this work is not to develop the tools but the process. This model (6) is based on the structural elements such as bulkheads and watertight decks as well as the type of space.

$I_C = N_{BHDs} + N_{WTDKs} + W_{COM} + F_C$	(6)

Where:

N_{BHDs} is total number of bulkheads above and below the bulkhead deck
N_{WTDKs} is number of watertight decks above the main deck
W_{COM} is width of the corridor between accommodations and
F_C is fitting cost, which is space specific.

4.4 Results

All the values were normalised so as to be smaller than the unit for ease of comparison. A summary of the rating of each design for each goal is displayed in Table 2. The following three figures show the correlations between the design objectives

Table 2. Results summary.

	Index A	I_V	I_C
des1	0.66391	0.900205	0.597
des2	0.80204	0.838385	0.880
des3	0.79577	0.792456	0.851
des4	0.75851	0.954596	0.793
des5	0.75657	0.902312	0.763
des6	0.82416	0.804196	0.952
des7	0.81943	0.730325	0.906
des8	0.76935	1	0.864
des9	0.76466	0.908161	0.818
des10	0.68587	0.870215	0.606
des11	0.83742	0.803439	0.902
des12	0.83013	0.759781	0.872
des13	0.78371	0.909554	0.814
des14	0.78148	0.860129	0.785
des15	0.85302	0.766297	0.973
des16	0.85048	0.696444	0.927
des17	0.79328	0.942169	0.886
des18	0.78532	0.856283	0.840
des19	0.69694	0.842184	0.619
des20	0.85401	0.773002	0.928
des21	0.84847	0.730073	0.898
des22	0.80446	0.88646	0.827
des23	0.79873	0.837249	0.798
des24	0.86415	0.735331	1.000
des25	0.8604	0.666969	0.953
des26	0.82882	0.923557	0.900
des27	0.81441	0.837731	0.853

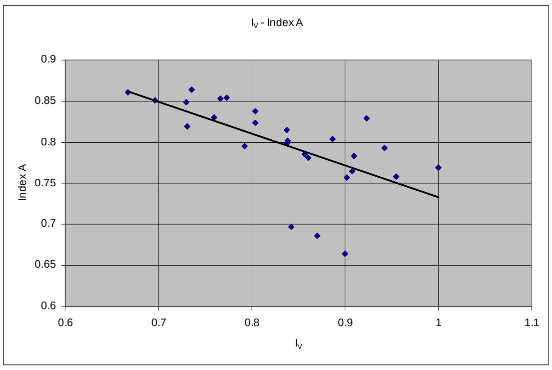

Figure 11. Volume Index – Index A.

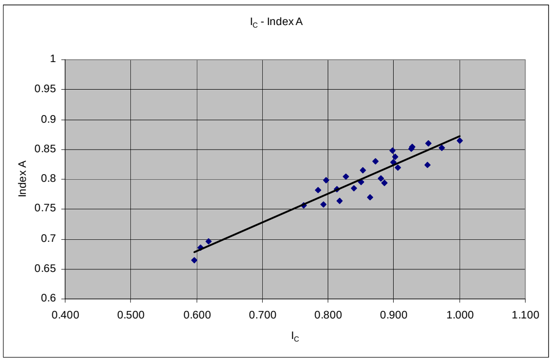

Figure 12. Cost Index – Index A.

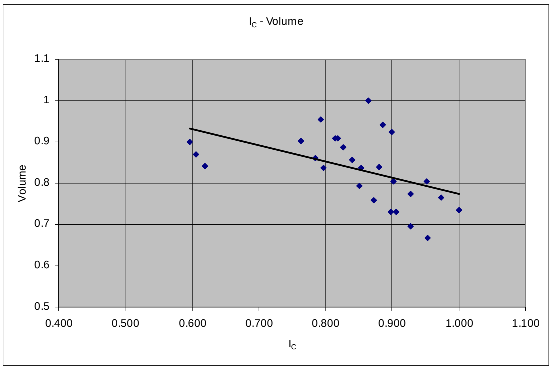

Figure 13. Volume Index – Cost Index.

Figure 11 shows how survivability decreases as compartment volume increases, in other words functionality increases. Figure 12 indicates how survivability affects cost – increased survivability leads to increased cost and Figure 13 suggests how cost decreases as compartmentation decreases (as steel weight decreases).

4.5 Optimisation

Having these results, the designer, in cooperation with the ship owner, can then choose the most important issues that need to be addressed in the on-going design so they can decide which trade-offs between goals they have to make in order to obtain an optimised design. A Pareto finding software can derive the optimum designs out of the design variants produced prior to any decisions being made by the design team. Each of the Pareto-optimal sets will be better in some way than the rest (Figure 14). It is at this point that the choice will have to be made on the importance of all pertinent goals. For example one might want to maximise safety at all costs or barely make it comply with safety regulations in order to have the cheapest, most functional design. This is just the first loop of the optimisation process, thus the seemingly optimal designs can be more than one. After decision making there will be another set of Pareto-optimal designs, better still than the previous and possibly (although not necessarily) lesser. Whatever the case, such choices can be made at an early stage when they are mostly inexpensive.

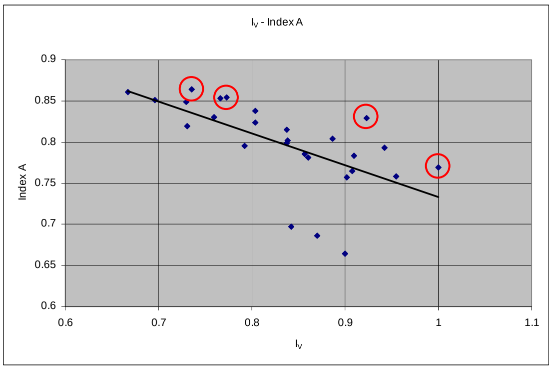

Figure 14. Pareto-optimal designs with regards to volume and survivability.

5. FUTURE WORK

This case study presented here is just a demonstration of how helpful Goal-Based Design can be in the difficult task of designing a successful ship. In addition, the goals selected and the tools used (however basic) were meant to indicate current efforts at the Ship Stability Research Centre to facilitate progress in Design for safety and Risk-Based Design by demonstrating how safety (risk) could be accommodated within a Goal-Based Design framework that concurs with contemporary understanding and developments in ship design.

To this end, work is progressing at speed to improve on survivability models and to derive meaningful parametric models addressing functionality and costs / earnings. Some simple models for the latter are already available from research undertaken during SAFEDOR. As a general statement, develop-ment of suitable models for risk, cost /earnings and performance is paramount.

Notably, a Virtual Integration Design Platform has already been developed as part of the SAFEDOR Project to facilitate this process, including design decision aiding tools capable of capturing experiential as well as knowledge from first-principles tools prior to or generated during the design process, Puisa (2009).

All this efforts highlight an attempt to render ship design truly holistic and in so doing capture and benefit from its complexity.

6. CONCLUSIONS

Naval architecture has just started to change after a long period of apparent stagnation. Deterministic concepts in force for years and reactive regulations have dominated ship design, leaving little room for improvement and innovation. However there is a shift in the way of thinking. Both the means and incentives are there for great achievements and designers have to exploit the opportunity. Goal-Based Design can help in this direction by offering a versatile tool for design creation. However, care has to be taken so that the tools and objectives used are adequate to tackle the tasks they are subjected. When applied correctly, Goal-Based Design can result in the best compromise between safety, performance and cost whilst nurturing innovation.

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