NATIONAL TECHNICAL UNIVERSITY OF ATHENS
NAVAL ARCHITECTURE AND MARINE ENGINEERING
DIVISION OF SHIP DESIGN AND MARITIME TRANSPORT

<u>THESIS</u>

SENSITIVITY OF ATTAINED SUBDIVISION INDEX (A) IN GEOMETRIC CHANGES IN THE GENERAL ARRANGEMENT OF CRUISE SHIPS

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With this thesis that I was assigned in September 2006 and finished in October 2007 I was given the opportunity to deepen into the new harmonized probabilistic regulations for damage stability and examine alternative designs applicable on cruise ships in order to increase survivability.

I would like to thank Professor Konstantinos Spyrou for giving me the opportunity to carry out this research and for his assistance. Furthermore I would like to thank Professor Drakos Vassalos for the eye opening discussions between us and for giving me some of his very precious time.

In addition I would like to thank the department of Naval Architecture and Marine Engineering of the University of Strathclyde in Glasgow for letting me use their facilities and resources and for the help of their staff.

I also thank my family for their understanding, patience and support all these years of my studies and my friends for all the good times and support.

Last but not least a big thanks to my dear Calliope for always believing in me and for always being there when needed the most.

Dedicated to Marinos

Evangelia

Antonis

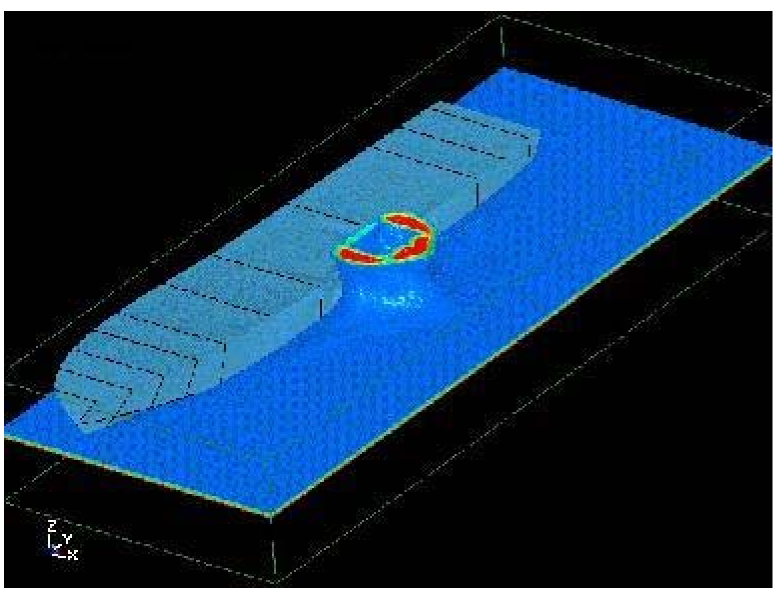
and

Calliope

Contents

Abstract

"Total freedom it appears is hard to cope with and a helping hand is needed to guide cross the line from prescriptive to goal seeking design and regulation." [1]. Based on this statement, this research is an attempt to help the naval architect on the chaotic task of building an innovative, competitive and above all safer ship. The target is to compose a general guideline anyone can use, to know exactly in which way to face their efforts in order to get the optimum Index A, without compromising other characteristics such as the cost and functionality of their design project. Alternatively, this guideline could help obtaining the required index A by minimizing cost and lightship as well as increasing functionality. Towards this direction, an extended study has been done, upon an already existing design. By expressing several of its geometric features, such as the number of bulkheads, the double hull's clearance and the side casings' length, parametrically and then changing their values, the effect of each change could be measured, in terms of Index A. The results of hundreds of alternative arrangements were treated with multiple regression tools to measure the weighting factor of more than ten parameters in the overall process. The next step of this research and an idea of a postgraduate study could be the extend of the outcome to include all known ship types as well as the design of a high survivability ship, say with A=0.99 to prove the rightness of the outcome.



Introduction

In the simplest of levels, the dilemma of prescriptive SOLAS-minded designers can be demonstrated in Figures 1 and 2 below:

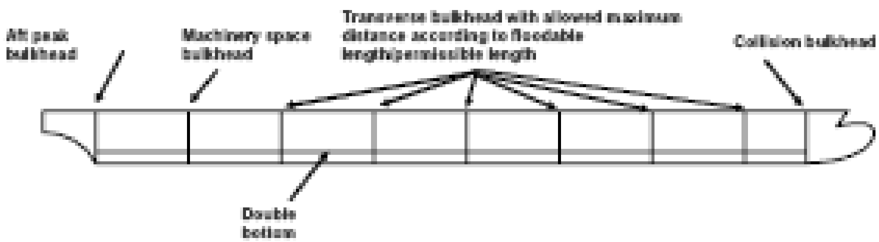


Figure 1 Prescriptive design

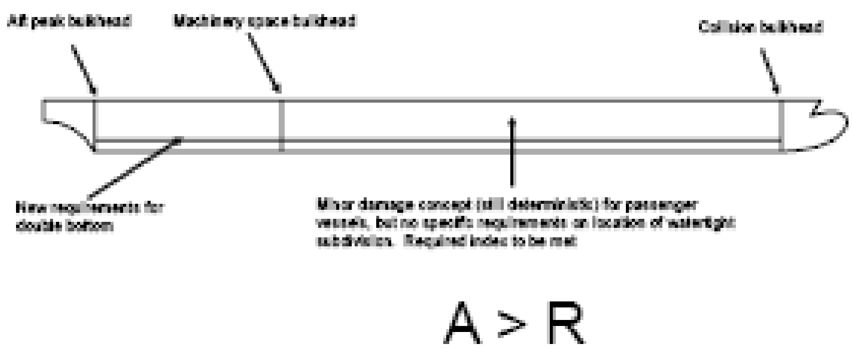


Figure 2 Goal seeking design

It is quite obvious that internal subdivision arrangement is a key issue affecting ship performance, functionality and safety, all of which have to date been catered through the provision of rules and regulations, reflecting in essence codification of best practice. Throwing this away and leaving on the table a blank sheet, makes ship subdivision a very difficult problem indeed. This was essentially the problem addressed in the EU project ROROPROB [9].

Chapter 1. Background

1.1. Historical approach

One of the most critical problems of all marine structures -and particularly ships because of their dynamic nature- is the loss of buoyancy and/or stability in case of collision or grounding. The problem gets even more complicated if taken into consideration that ships operate in an inhospitable and unpredictable environment. To make things worse, evacuation in case of an accident is hazardous itself.

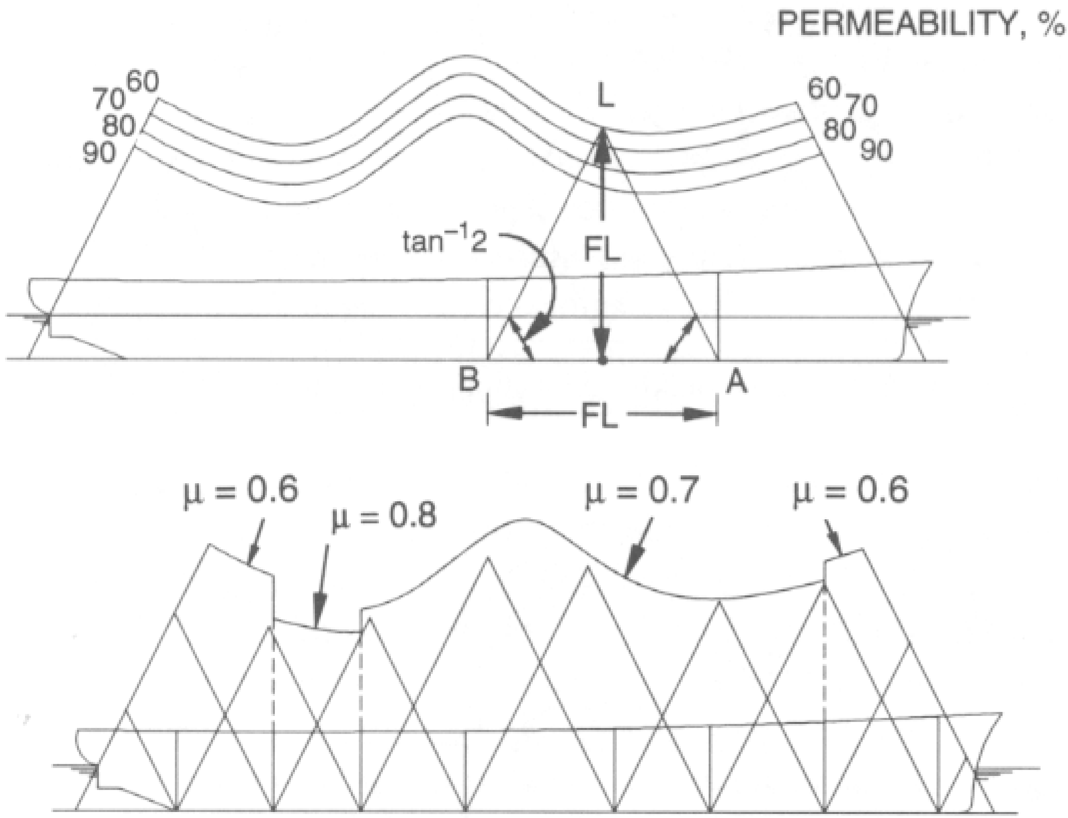
Picture 1.1
Ship operating in
hazardous conditions

This had always been a problem but over the previous century the situation got a lot worse. Victim numbers increased dramatically as more and more people used ships not only as a means of transportation but for recreation as well. Huge quantities of merchandise were lost, as sea trade grew, resulting in major economic impact, both on carriers and clients, as well as society itself. Additionally, as society evolves, the need for safety grows, thus leading to the reduction of acceptable risk. The means and knowledge though of the time seemed unable to quantify risk in order to reduce it.

It is surely more than a few times that we have seen accidents happen, many times under the best possible conditions when nothing should have gone wrong. There is an infinite number of hazards that a ship can come across in its life cycle. One of the most common among them is the so called human factor. This factor is more of an operational nature and the possibility of a mistake occurring will always be the same but what if the consequences of that mistake can be minimized? Can one be optimistic enough to believe that ships can one day become "mistake proof"?

Picture 1.2 The accident of the cruise ship "Sea Diamond" in Thira 2007

People started asking themselves that question quite early in the past century, mainly after major accidents. Research was done around the causes of every accident for the first time resulting in the deeper understanding of the mechanisms that led to an accident, itself resulting in the institution of rules and regulations. The first rules aiming at the improvement of ships' survivability were mainly deterministic. Based on experience, the concept was that a ship should have enough residual buoyancy to be able to sustain a flooding in one or several of its compartments (depending on the type of its "cargo"). The process was named floodable length calculation and the compartmentation was done according to the maximum length of the ship that could get flooded without the ship's drought exceeding the margin line. The margin line lies 76mm below water tight deck. The dimensions of the breach though were deterministic as well, restricting to a minimum the damage scenarios. Unfortunately it was experience again that showed this was not enough as such measures could be effective only on perfect weather conditions, a very rare state in reality and for a very limited number of cases. Scientists were probably not ready yet to deal with probabilistic issues, so early attempts of revising these first rules lead to the consideration of stability. However, just as buoyancy, stability was considered only superficially and as a result, insufficiently.



Pictures 1.3&1.4 Floodable length calculation

Deterministic rules left designers little freedom to make innovations. On the other end, most designers were content by simply complying with the rules so little progress was made over the years. Such was the case until very recently when alternative designs could be accepted as long as they were proven at least equivalent to the deterministic ones. Not until 1974, were probabilistic rules instituted but there was little confidence in them. The probabilistic damaged stability assessment concept was originally introduced by K.

Wendel (1960) more than 40 years ago. It was adopted by the International Maritime Organization in IMO SOLAS A.265 (VIII) (1974) as an alternative to the deterministic concept for the assessment of passenger ships and was much later reaffirmed by IMO Resolution MSC.19 (58) (1990) as to its mandatory application to all dry cargo ships built after February 1992, as laid down in SOLAS B-1 Reg. 25. The probabilistic damage stability concept is expected to become the future damaged stability regulatory standard for all types of ships through the currently under completion harmonized damage stability rules (see IMO-SLF46, 2003).

What is more computational power proved inadequate for the calculations needed appointing probabilistic approach inconvenient. None of the previous rules though could really evaluate safety. One could only be informed of whether a ship was safe or not and this only subjectively. As computational power increased over the past few years, probabilistic rules started to become more applicable. The need was expressed to surpass deterministic rules. So, new probabilistic rules were evolved, to include passenger ships, as a means of measuring safety in all (or most) possible scenarios. Computers' advance was so dramatic that it is now considered easy to make millions of calculations. Almost simultaneously the development of design packages and simulators led to more accurate results and minimized risk, not only in damage stability but in all hazardous scenarios such as fire and flooding. Ever since, major improvement is being made in ship damage stability and survivability.

1.2. The future is probabilistic

The result of the latest progress is Attained index of subdivision or Index A and has been developed to address the need to quantify safety [13]. Index A is basically a sum of all the possible damage scenarios times the possibility for each different scenario of surviving. Loading conditions are also taken into account in order to improve outcome. A design is accepted if Index A is greater than a required index R.

$$A = \sum_{j=1}^{J} \sum_{i=1}^{I} w_j \cdot p_i \cdot s_{ij} \,, \qquad A>R$$

The principal probabilistic elements mentioned in the above equation are the factors 'w_i', 'p_i' and 's_i'.

'w_i' is the loading condition. Usually Index A is calculated for 3 different drafts and summarized with a weighted formula.

'p_i' is a factor which estimates the probability of the longitudinal extent of damage;

's' is a factor which is a measure of survival probability. When s = 0, this means that there is no contribution to the index 'A' for the damage case being considered. When s = 1, this means that all the conditions for survival given by the specified residual stability criteria are fully met.

$$s_i = k \cdot \left[\frac{GZ_{\max}}{0.12} \cdot \frac{Range}{16} \right]^{\frac{1}{4}}, \quad GZ_{\max} \leq 0.12m, \quad Range \leq 16^o$$

'A' is Attained Subdivision Index,

'R' is Required Subdivision Index, R in probabilities damage stability rules, if the attained subdivision index A is greater or equal to required subdivision index R, the vessel fulfils stability requirements. For passenger ships, the R is calculated as follows (preliminary information):

$$R = 1 - \frac{5000}{L_S + 2.5 \times N + 15225}$$

where: L_S = subdivision length in meters
N = N1+2 x N2

N1 = the number of persons whom lifeboats are provided
N2 = number of persons (pax+crew) the ship is permitted to carry in excess of N

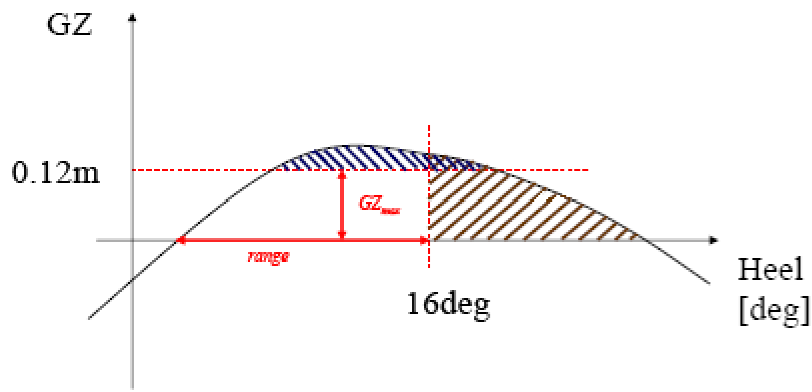


Figure 1.1
Stability limits in the new formulation

The importance of Index A is still partly unveiled. It is believed that Index A has many more applications in ship design than it was initially conceived to have. For example it was not since very recently that Index A proved to have indissoluble relation to the probability of a ship to capsize within 3 hours which is the time postulated by IMO. This deterministic number is inappropriate since time to capsize can only be predicted in probabilistic terms and the correct term should be "time to capsize within 3 hours with probability of x%". The marginal probability distributions for time to capsize tend to asymptotic values defined by (1-A). [1]

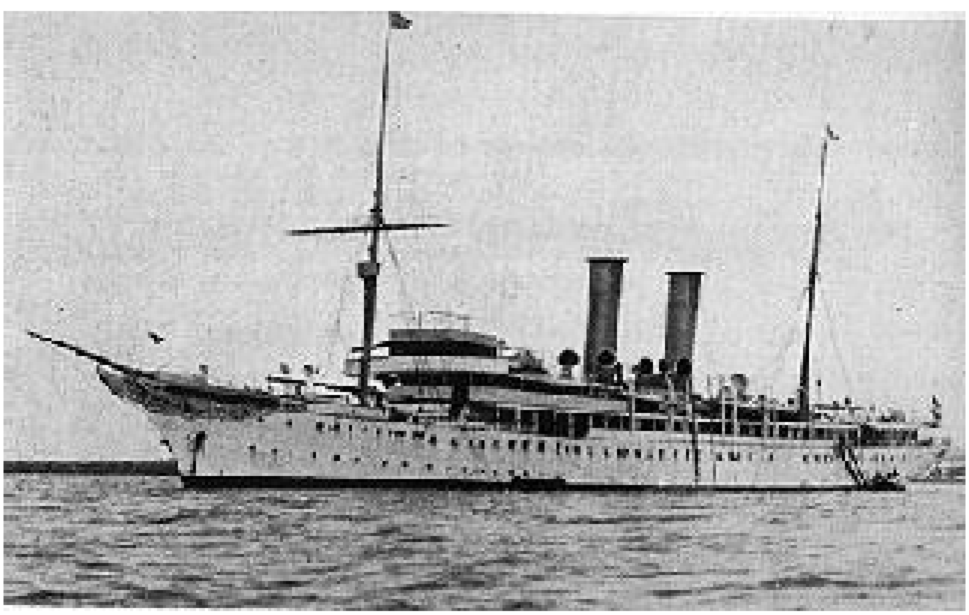
Another outcome of the same research shows that 15% increase in Index-A of the hypothetical cruise ship, results in a 60% reduction in the probability to capsize within 3 hours.

The ability to estimate the probability of the time to capsize (in fractions of a second) could prove a massively important tool to aid decision making in emergencies, particularly when knowledge specific to the accident in question is accounted for and resolution of the model is enhanced by the time domain simulation results.

1.3. Cruise ships

A cruise ship or a cruise liner is a passenger ship used for pleasure voyages, where the voyage itself and the ship's amenities are considered an essential part of the experience. Cruising has become a major part of the tourism industry, with millions of passengers each year. The industry's rapid growth has seen nine or more newly built ships catering to a North American clientele added every year since 2001, as well as others servicing European clientele. Smaller markets such as the Asia-Pacific region are generally serviced by older tonnage displaced by new ships introduced into the high growth areas.

Cruise ships operate mostly on set roundabout courses, returning with their passengers to their originating port. In contrast, ocean liners doing "line voyages" in open seas are strongly built to withstand the rigors of transoceanic voyages, and typically ferry passengers from one point to another, rather than on round trips. Some liners also engage in longer trips which may not lead back to the same port for many months. The first vessel built exclusively for this purpose was the Prinzessin Victoria Luise, commissioned by Albert Ballin, general manager of Hamburg-America Line. The ship was completed in 1900.



Picture 1.5 Prinzessin Victoria Luise (1900)

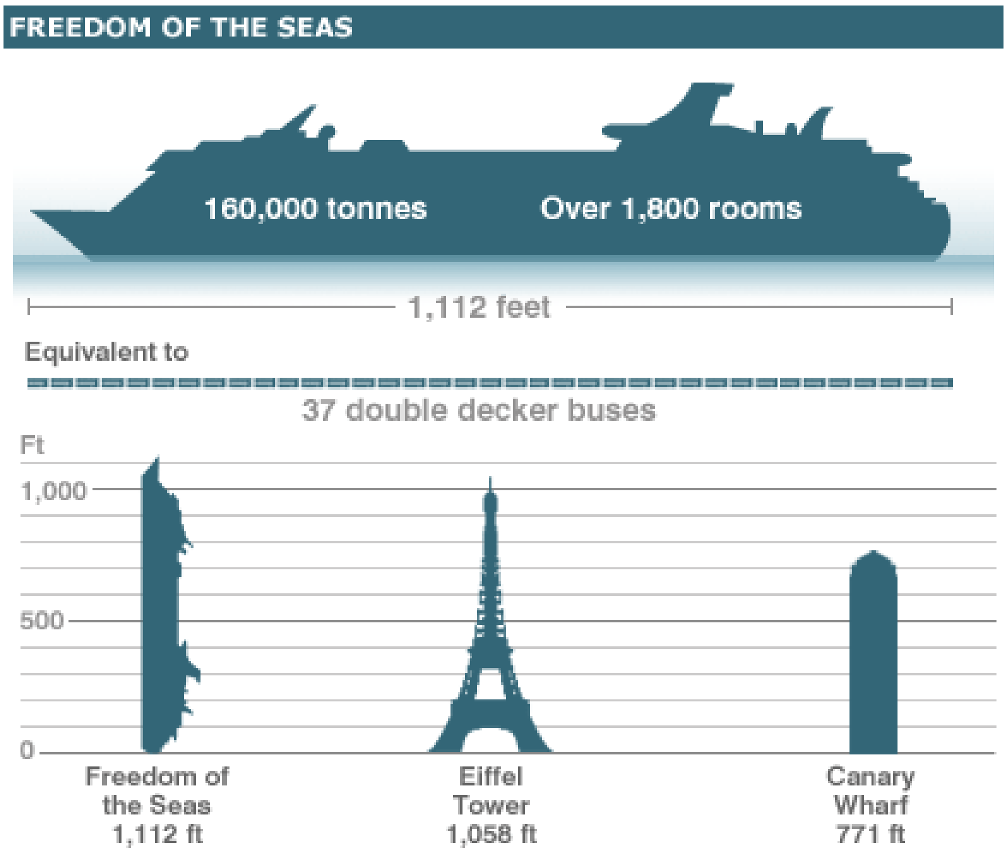
The practice as known today grew gradually out of the transatlantic crossing tradition, which, despite the best efforts of engineers and sailors into the mid-20th century, rarely took less than about four days. In the competition for passengers, ocean liners added many luxuries — most famously seen in the Titanic, but also available in other ships — such as fine dining, well-appointed staterooms, and so forth.

In the late 19th century, Albert Ballin, director of the Hamburg-America Line, was the first to make a regular practice of sending his transatlantic ships out on long southern cruises during the worst of the winter season of the North Atlantic. Other companies followed suit. Some of them built specialized ships designed for easy transformation between summer crossings and winter cruising.

With the advent of large passenger jet aircraft in the 1960s, the vast majority of intercontinental travellers switched from ships to planes. There are some however, who enjoy the few days of luxury and enforced idleness that a liner voyage affords, so a small niche market has remained for transatlantic voyages. Excluding this exception, the ocean liner transport business crashed. Cruising voyages however gained in popularity; slowly at first but at an increased rate from the 1980s onwards. Initially the fledgling industry was serviced primarily by redundant liners, and even the first purpose built cruise ships were relatively small. However, after the success of the SS Norway (previously the SS France, re-launched in 1980) as the Caribbean's first "super-ship", the size of these vessels has risen dramatically to become the largest passenger ships ever built.

The 1970s television show The Love Boat, featuring Princess Cruises' since-sold ship Pacific Princess, did much to raise awareness of cruises as a vacation option for ordinary people in the United States. Initially this growth was centred around the Caribbean, Alaska and Mexico, but now encompasses all areas of the globe. As of 2004, several hundred cruise ships, some carrying over 3,000 passengers and measuring over 100,000 gross tons, ply routes all over the world. For certain destinations such as the Arctic and Antarctica, cruise ships are very nearly the only way to visit, a fact that is the primary attraction for many tourists.

Present-day cruise ships are organized much like floating hotels, with a complete "hospitality staff" in addition to the usual ship's crew. It is not uncommon for the most luxurious ships to have more crew and staff than passengers.



Picture 1.6 Super-size cruise ships

As with any vessel, adequate provisioning is crucial, especially on a cruise ship serving several thousand meals at each seating. Passengers and crew on the Royal Caribbean International ship Mariner of the Seas consume 20,000 pounds (9,000 kg) of beef, 28,000 eggs, 8,000 gallons (30,000 L) of ice cream, and 18,000 slices of pizza in a week.

Many older cruise ships have had multiple owners over their lifetimes. Since each cruise line has its own livery and often a naming theme (for instance, ships of the Holland America Line have names ending in "-dam", e.g. MS Statendam, and Royal Caribbean's ships' names all end with "of the Seas", e.g. MS Freedom of the Seas), it is usual for the transfer of ownership to entail a refitting and a name change. Some ships have had a dozen or more identities.

Picture 1.7
Swimming pools and water games are common ground among modern cruise ships

Picture 1.8
Promenade decks that resemble malls

Cruise ships and former liners often find employment in applications other than those for which they were built. A shortage of hotel accommodation for the 2004 Summer Olympics led to a plan to moor a number of cruise ships in Athens to provide tourist accommodation. On September 1, 2005, FEMA contracted three Carnival Cruise Lines vessels to house Hurricane Katrina evacuees.

The primary purpose of cruise vessels is the entertainment and transport of passengers. To fulfil this purpose, the noise and vibration level aboard as well as the motions of the ship during transit or anchorage should be minimal. Furthermore, the ship is to be able to operate independently in widely varying operational conditions. This poses stringent demands on the harbour manoeuvring capability. Since the loading condition of cruise vessels changes only marginally during the service, the hull form and bulbous bow of these ships can effectively be optimized from a powering point of view.

The first important step in hull form optimization is to recognize which type of vessel is to be optimized. The operability and performances of the ship must be considered in details, other points of intention are ports limitations, ship owner requirements, slamming, vibrations and structural requirements. In the general the optimization is focused on minimizing the resistance by mainly reducing the wave resistance.

Chapter 2. Problem definition

Although certainly a better and more complete approach than previous ones, attained subdivision index (Index A) also has its weak points. For example during the calculation process some geometric specifications are treated as more important than others. For example longitudinal subdivision is taken more into account than transverse. This is against common sense of the naval architect since longitudinal subdivision tends to create asymmetries in case of flooding. It has already been proven that transverse subdivision under watertight deck (i.e. longitudinal bulkheads and/or double hull) can work in favour of survivability without creating asymmetries, provided that there are cross connections bridging portside and starboard compartments. Extension of the watertight envelope above watertight deck in the form of either side casings or partial bulkheads can also benefit ship survivability because when flooding occurs there will be sufficient buoyancy high and wide.

However, there is no real incentive for the designer to consider such high survivability measures because the real benefit of them is partly ignored in the calculation of A [3]. For the calculation of the possibility p_i of a damage scenario to occur, all possible damage scenarios are considered (including breaches positioned higher than the bulkhead deck). On the contrary, it is quite peculiar that in the formulation of s_i, what affects outcome the most is subdivision below watertight deck, thus neglecting the importance of expanding the watertight envelope above bulkhead deck.

During the s-factor formulation (survivability) the limits in the restoring curve parameters ignore partly ship geometry, particularly so geometry that is known to lead to high survivability (figure 2.1), [2]. In addition the intermediate stages of flooding are not considered. And while this is of no significant importance in case of simple ships such as crude oil tankers and bulk carriers, it is quite a major neglect for ships with complex geometry, such as Ro-Ro’s and Cruise ships (figure 2.2).

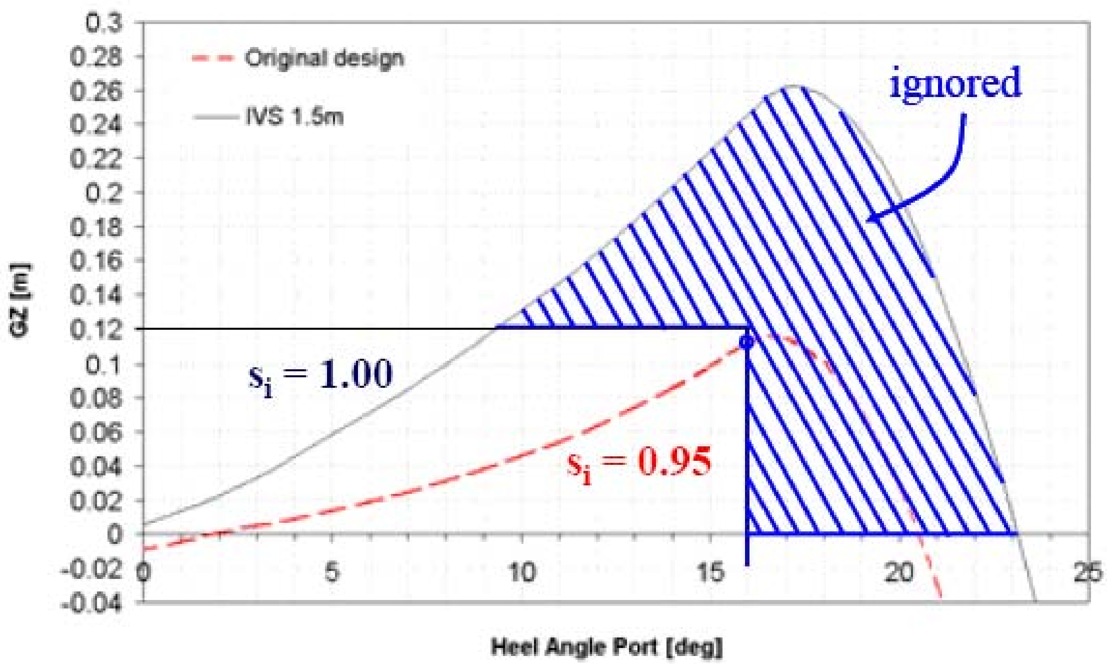


Figure 2.1 Real survivability enhancements ignored

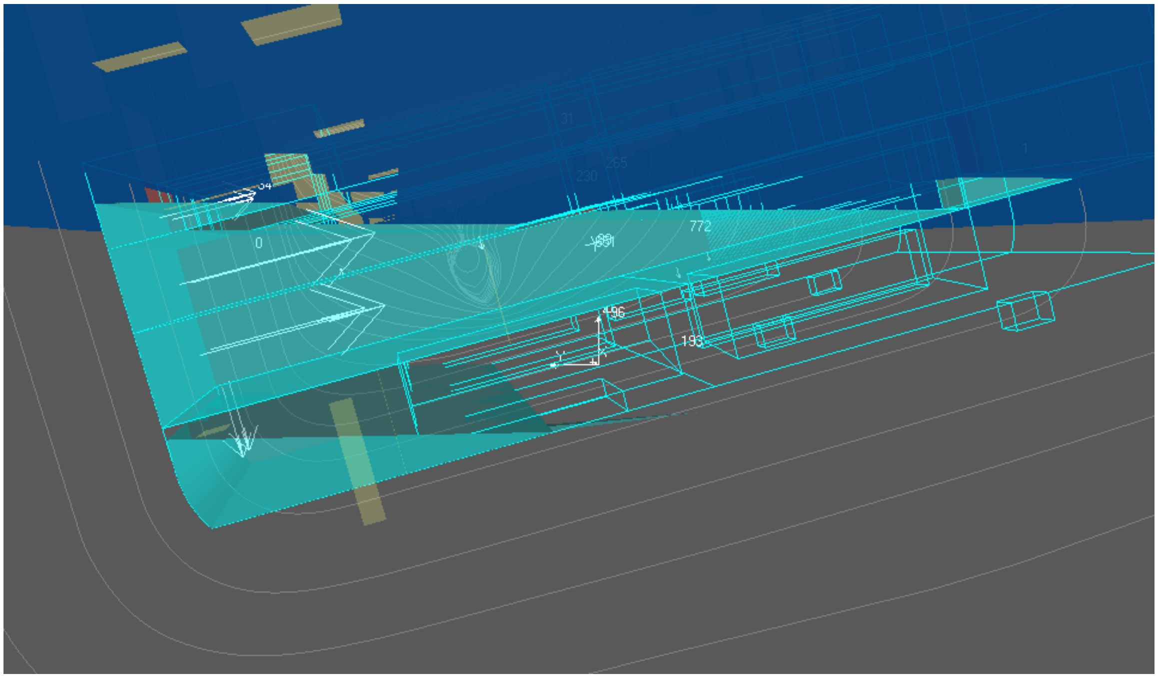


Figure 2.2 Intermediate stages of flooding

Chapter 3. Aims of the thesis

The overall aim of the thesis is to gain a fundamental understanding of the key parameters that affect passenger ship subdivision and layout configuration that lead to high survivability ships. Calculation is to be done according to probabilistic rules for ship subdivision and to be verified by state-of-the-art numerical simulation tools, with a view to providing suitable guidelines to ship designers and regulators.

To this end, the following specific objectives will be targeted:

1. Gain an in-depth understanding of the new harmonised probabilistic rules; thus highlighting the key components determining damage survivability and any gaps needing further attention.

2. Use a typical passenger ship (cruise liner) as a platform to set up an optimisation problem for maximum survivability (maximum Index A), by using parametric subdivision and layout arrangements (including all relevant decks) in a typical Naval Architecture CAD package (e.g. NAPA).

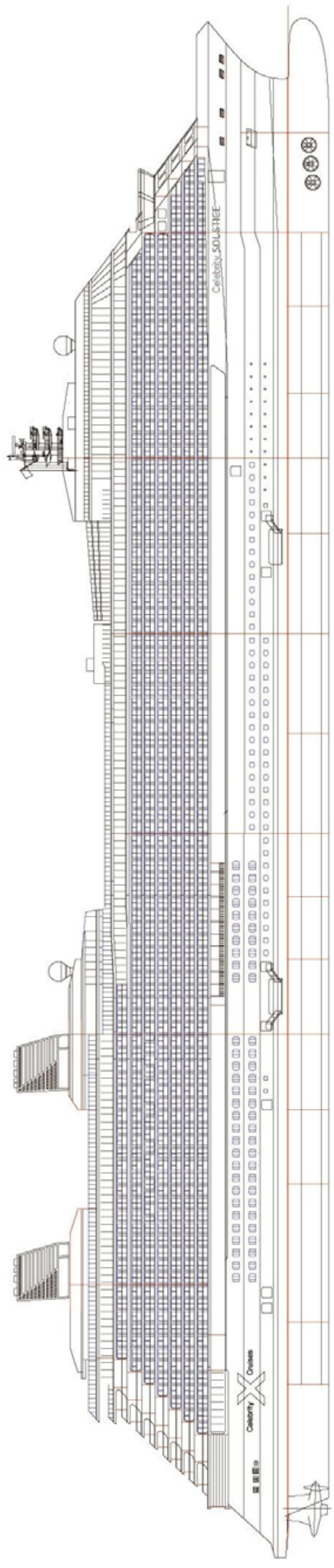
3. Set up a scheme to enable a systematic investigation of all possible subdivision arrangements (transverse, longitudinal, continual) and ship layout (deck layout, side casings size and position, central casings, partial bulkheads, semi-watertight/watertight doors) thus identifying the contribution of each to Index A and enabling the establishment of a relationships between Index A and key Subdivision/layout features (e.g. bulkhead spacing per ship length).

Chapter 4. Method of approach

4.1. The model

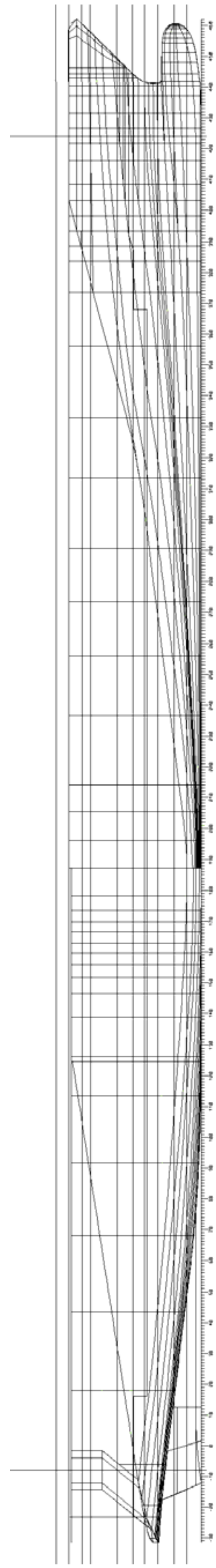
Picture 4.1 Celebrity Solstice

The model used for the calculations is a cruise ship that's being built at the time and is called Celebrity Solstice. She's a state of the art ship built up to the highest standards and according to probabilistic rules. She is being built on account of the Royal Caribbean Celebrity X Cruises. She is expected throughout the world with great anticipation since she is supposed to introduce several innovative features such as a contemporary class of balcony staterooms with spa-inspired amenities, more spacious rooms and indoor swimming pools from the accommodation point of view. On the other hand, from the naval architecture point of view it wouldn't be an exaggeration to consider her as a miracle. She is probably the first ship to adopt the specific arrangement as far as the engine rooms are built. One is in front of the other taking up space that couldn't and shouldn't be used in any other way. This arrangement has the benefits of leaving the outer space for accommodation (crew mostly) as well as hiding the engine room several meters away from the outer hull and away of damage and flooding in most damage scenarios. What made this particular arrangement possible is the fact that the ship uses azipods for its propulsion so there is no need for direct connection from the engine to the propeller. This particular feature can also be seen on picture 4.2 pointed out by the two funnels put one behind the other. Another benefit of the specific design is the centralization of mass around the centre line of the ship thus leading to far better behaviour in waves and manoeuvring. Despite not being the largest vessel in her category, the Solstice is expected to have the largest room for her guests, providing spacious staterooms and wide and long promenade decks overcoming even the barrier of the 50m fire zones, specified by the regulations, displaying an alternative design better than the prescriptive one. All in all she can be described in one word as a herald. A herald of the future in cruise ship industry.



Picture 4.2
On the left is the side drawing of the Celebrity Solstice.
Some of the 20 bulkheads are visible as well as the fire zones

Picture 4.3
On the right is the drawing of its hull with the decks as derived from NAPA.

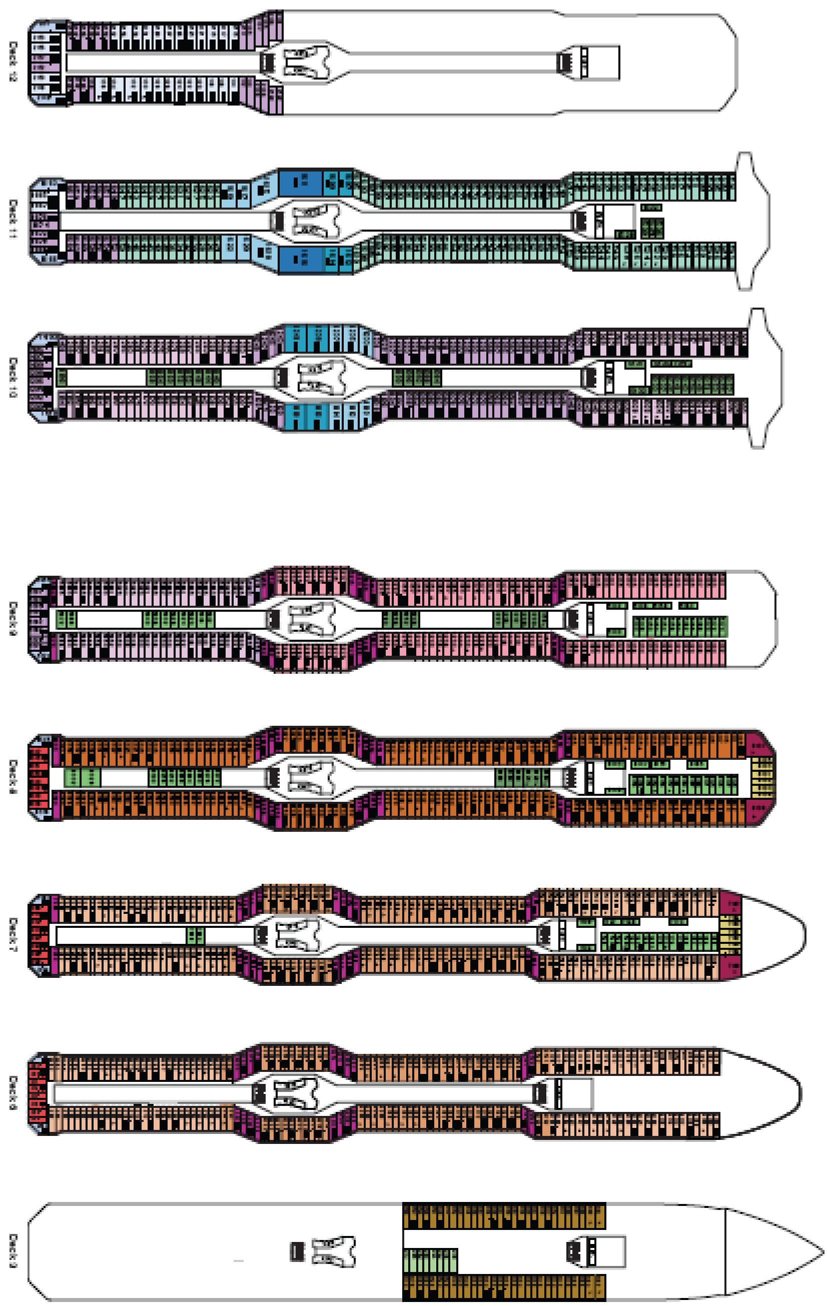


L_{OA} =	318.41	m
L_{BP} =	293.7	m
T_{DWL} =	8.3	m
T_{MAX} =	8.6	m
B_{MAX} =	36.8	m
B_{REF} =	36.8	m
H_{MD} =	11.3	m
H_{MAX} =	60	m
C_B =	0.6362	
Displacement =	58,751.2	mt
N_{PA} =	3148	

Table 4.1 Principal dimensions of the Solstice

frame fore	spacing	frame aft.
-	0.64	54
54	0.69	58
58	0.64	134
134	0.69	138
138	0.64	198
198	0.69	202
202	0.64	262
262	0.69	266
266	0.64	318
318	0.69	322
322	0.64	390
390	0.69	394
394	0.64	-

Table 4.2 Frame spacing of the Solstice



Picture 4.4
The layout of the Celebrity Solstice's decks. The central casing of the funnels and other machinery is clearly visible.

Of course all the previous is just an acquaintance with the model ship since what have been kept from her original design in NAPA are only the hull form, the initial loading conditions and some moments according to SOLAS and IMO regulations. These moments are: IMOWIND for weather, SOLASPASS for passengers, SOLASBOAT for rescue boats, WIND for wind and WIND20 for 20m/s wind and are presented in appendices 2 and 3

4.2. General arrangements and subdivision

All different general arrangements are produced and treated in NAPA environment. The several arrangements were created by macro-commands (macros). These produced the subdivision, compartmentation, room definitions and zones of flooding that a GA consists of, as well as run the sequence of index A calculation. The results were saved in excel spreadsheets for future process. All the macros are available as appendices at the end of the thesis, as well as the results in raw form (as saved first time).

4.2.1. Stages of the project

The project is divided in two stages depending on the topology of the subdivision. In the first stage only subdivision below bulkhead deck will be taken into account in order to calculate index A. This consists of number of bulkheads, double hull and step raise of deck fore and after. The arrangement that produces the maximum index A will then be used to build upon it several other arrangements above bulkhead deck to check if further increase of index A can be achieved by extending the watertight envelope. This is referred to as stage 2.

4.2.1.1. Stage 1

As it is developed in previous paragraph, in stage 1 only subdivision below bulkhead deck has been examined. The parameters set for this study are the following 4:

<u>1. Number of bulkheads.</u> This parameter is set to have values from 10 to 50 with a step of 2. Although 50 bulkheads is usually too many for an ordinary cruise (and not only) ship, a research to this extend was necessary to prove wrong of the initial belief that index A would decrease after a certain number of bulkheads. As it turned out, index A shows clearly an asymptotic behaviour, in contrary to a previous research that had been done in bulk carriers, showing a maximum point.

2. Double hull clearance. This is the clearance between outer hull and inner hull. Inner hull is the plating extending from aftermost point of the ship to frame #424 in the front at a pre-specified clearance from outer hull. The values double hull is set to be are: a) B/10=3.68m (value prescribed by IMO), b) B/7.5 = 5.52m, c) B/5 = 7.36m (value in issue by IMO) and d) B/2.5 = 9.2m.

3. Raised deck length. It has been common knowledge for many years that a raise in the forward and after part of the watertight deck in the form of a "step", works in benefit of safety since it offers residual buoyancy in cases of high pitch angles. This parameter refers to the number of frames this raise extends to. Two different cases have been examined, one extending over 30 frames and another over 60 frames. This is the individual extend of each one of the forward and after raise. With a number of frames counting to more than 400, these values are approximately 7.5% and 15% of the ship's length respectively.

4. Raised deck height. In order to have a more complete picture of the issue of raised deck, it has been decided to investigate whether this particular feature can contribute more if it includes more than one decks. So the different cases for this feature will be two, one with the deck rising to the first deck above it and another that the deck raises to the second deck above it. These two decks are addressed to as "midupperdeck" and "upperdeck" and are located 3m and 6m above main deck respectively.

5. Cross connection. One set of experiments was conducted without cross connecting the portside and starboard compartments created by double hull, only to prove the great significance of this minor feature.

Figure 4.1 makes the above clearer and table 4.4 shows the different parameters along with their values and number of cases examined.

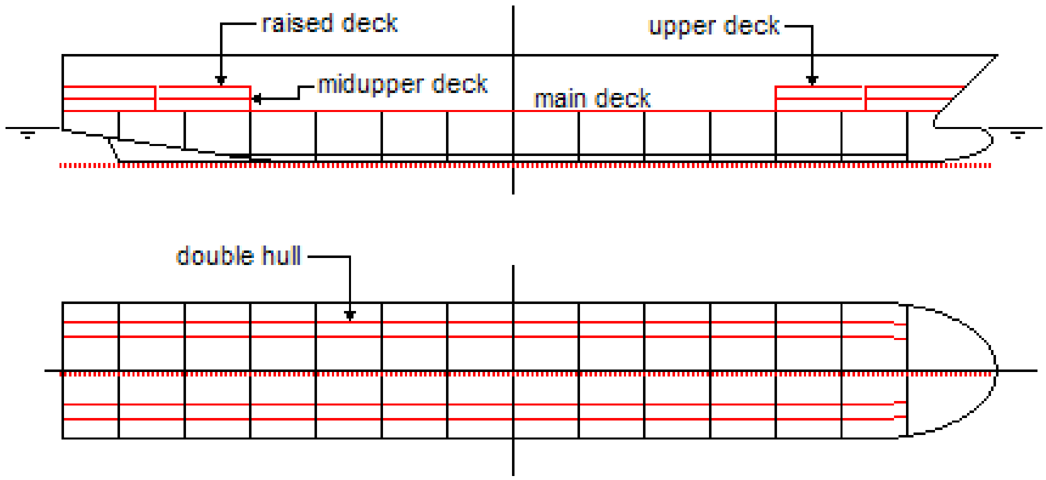


Figure 4.1 The various arrangements for stage 1

Item	values	#
bulkheads	N = 10 - 50 (step 2)	i=21
double hull clearance	0, B/2.5, B/5, B/7.5 or B/10	j=5
raised deck length	0, 5% or 10%L_{BP} (0, 30, 60 frames)	k=3
raised deck height	1 or 2 decks	l=2
Cross connection	0 (yes) or 1 (no)	+21
Total for hull:		i*j*k*l+21= 651
A_{opt}= MAX(A_{ijkl})		

Table 4.4 Values of parameters for stage 1

4.2.1.2. Stage 2

As previously mentioned, in stage 2 what has been examined is the extension of watertight envelope above subdivision deck. Several studies have been done pinpointing the right direction and going through them has more or less designated which parameters to use. In addition, since stage 2 is adding to overall safety it wasn't accounted as necessary to run all the cases from stage 1 once again so the case resulting in the optimum index A from stage 1 has been used as a base. Two are the main geometric features examined, side casings and partial bulkheads. Both are supposed to increase safety so their contribution has been put to the test. The following 7 parameters should have been used for the experiment:

1. Side casings' length. Side casings are features that are considered to add buoyancy high and wide. That is where it is most needed in case of flooding. It would probably be best if they extent to the whole length of the ship but since it is difficult both in terms of cost and layout flexibility, parameter length has been limited to 2 cases, one of 1/3 L_{BP} and another of 2/3 L_{BP} approximately.

2. Side casings' height. Parameter height of the side casings has been set to value 1 if it starts from bulkhead deck and extends to 1 deck above it or value 2 if it starts from bulkhead deck and extends to 2 decks above it.

3. Side casings' width. Side casings start from the outer hull but their width can vary. Two cases were examined, one with the width of the side casing being 5 m, to fit a cabin and a corridor (approximately 1/7.5 B_{REF}) and another with the side casing width being 10 m to fit 2 cabins and a corridor (approximately 1/2.5 B_{REF})

4. Side casings' subdivision. Compartmentation of side casings is under consideration here. Compartmentation must be kept down to a minimum since it is difficult to put watertight barriers above subdivision deck. So, two cases were examined, one with

watertight barriers being put above every bulkhead or every other bulkhead, thus creating 1 or 2 compartment subdivision.

5. Partial bulkheads' height. Partial bulkheads are features of great significance due to their manufacturing simplicity. It is usually common ground among this type of ships that on these decks straight above bulkhead deck and usually on the sides of the ship, crew cabins are placed, or even, less frequently, passenger cabins. As a result the ship is already subdivided to a certain extent inwards due to the cabin's length. So all a mechanic has to do is make the already existing partitions among the cabins watertight. Not all, just those needed, say every 5 or 10 cabins. The reason for not making the bulkhead run across the whole ship's beam is weight and the need for unrestricted promenade decks. Furthermore it is merely difficult for a ship to reach such heel angles without capsizing. The term height of the side casing refers to the number of decks the compartmentation extends above subdivision deck. As in side casings' case, the value is either one or two decks above bulkhead deck.

6. Partial bulkheads' width. As in side casings' case starting from outer hull and finishing at either 5 m (1/7.5 B_{REF}) or 10 m (1/2.5 B_{REF}).

7. Partial bulkheads' compartmentation. As in side casings case above every or every other bulkhead.

Figure 4.2 demonstrates the above and table 4.5 summates the parameters and their values. At the last row there is a summation for the whole number of experiments that were conducted for this project.

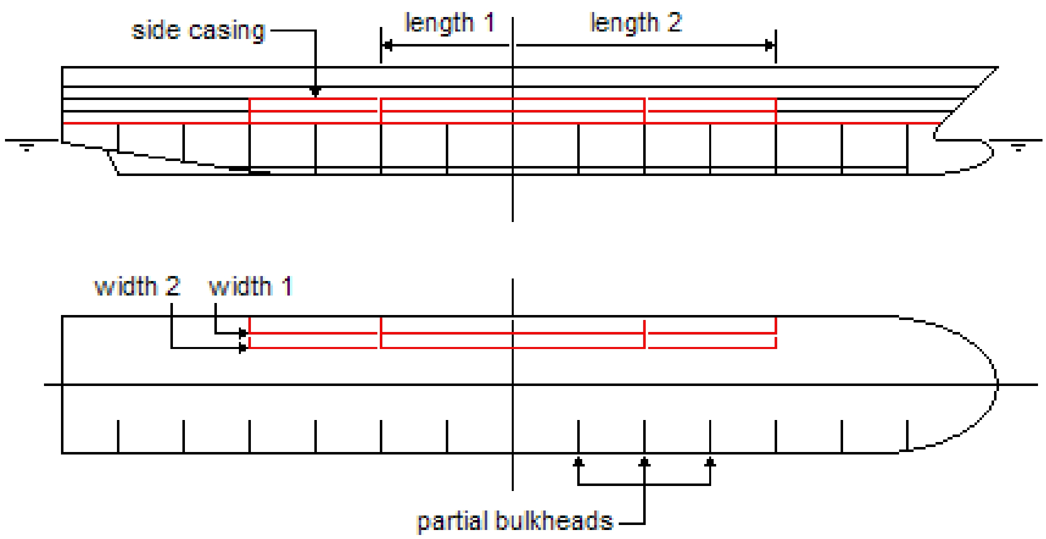


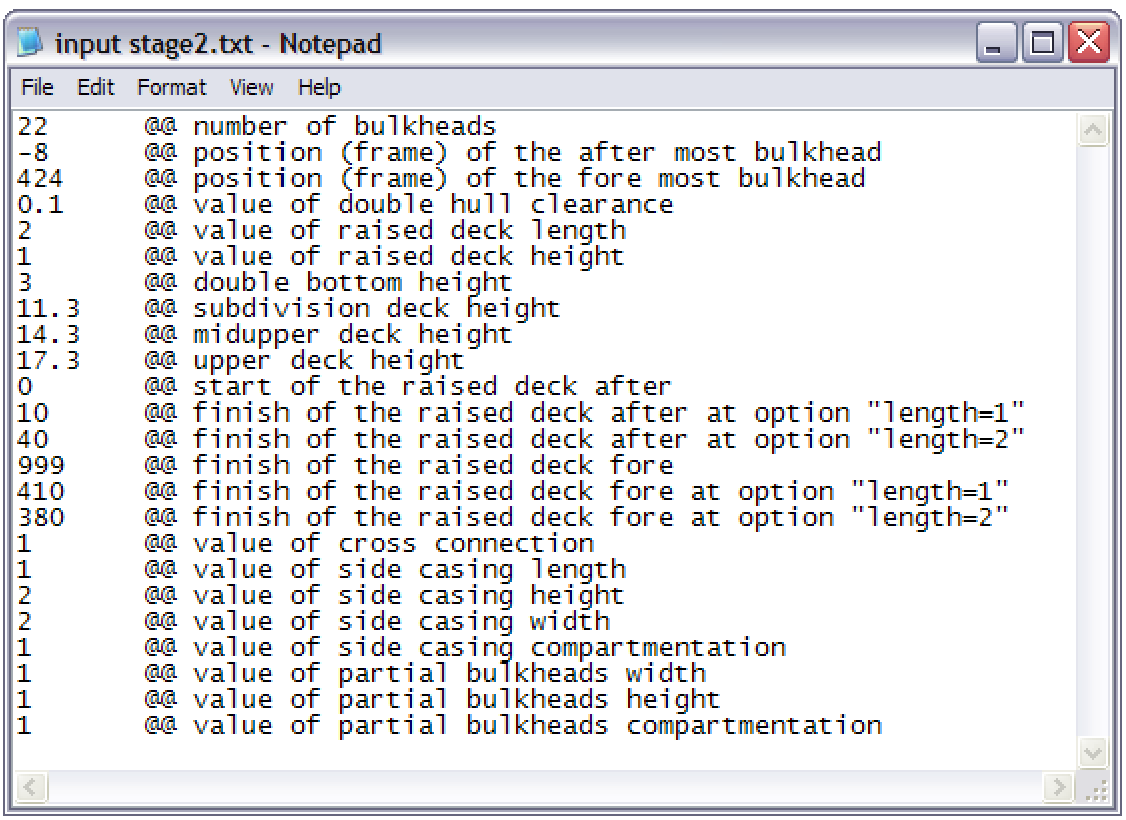
Figure 4.2 The various arrangements for stage 2

SC length	0, $1/3L_{BP}$ or $2/3L_{BP}$	m=3
SC height	1 or 2 decks	n=2
SC width	5 or 10 m	o=2
SC subdivision	1 or 2 compartments	p=2
Part. BHDs height	0, 1 or 2 decks	q=3
Part. BHDs width	5 or 10 m	r=2
Part. BHDs subdivision	1 or 2 compartments	s=2
Total for superstructures:		m*n*o*p*q*r*s =288
Total for project:		630 + 288 = 918
A_{max} = MAX($A_{mnopqrs}$)		

Table 4.5 Values of parameters for stage 2

4.3. The software

The software used for this investigation is NAPA. As its name suggests it is a naval architecture package which means that it can be used to create a ship along with all its subsystems and structures. NAPA can calculate various branches of the ship such as hydrostatics, hydrodynamics (manoeuvrability e.t.c.), structural strength and damage stability. That very last application of NAPA is what will be used the most in this study along, of course, with its ability to create arrangements using macros. A macro is a multi command algorithm which is supplied by the user to create the different layouts and arrangements needed. These are the arrangements whose Attained Subdivision Index will be calculated. An excel spreadsheet macro directs NAPA through the various macros, giving the order in which NAPA macros will run. The excel macro changes the values of the parameters in the input file. The values of the parameters are preset and given in the excel spreadsheet. About every possible combination of the parameters' values was used. An example of the input file is displayed below.


input stage2.txt - Notepad

File Edit Format View Help

```
22      @@ number of bulkheads
-8      @@ position (frame) of the after most bulkhead
424     @@ position (frame) of the fore most bulkhead
0.1     @@ value of double hull clearance
2       @@ value of raised deck length
1       @@ value of raised deck height
3       @@ double bottom height
11.3    @@ subdivision deck height
14.3    @@ midupper deck height
17.3    @@ upper deck height
0       @@ start of the raised deck after
10      @@ finish of the raised deck after at option "length=1"
40      @@ finish of the raised deck after at option "length=2"
999     @@ finish of the raised deck fore
410     @@ finish of the raised deck fore at option "length=1"
380     @@ finish of the raised deck fore at option "length=2"
1       @@ value of cross connection
1       @@ value of side casing length
2       @@ value of side casing height
2       @@ value of side casing width
1       @@ value of side casing compartmentation
1       @@ value of partial bulkheads width
1       @@ value of partial bulkheads height
1       @@ value of partial bulkheads compartmentation
```

Left of the @@ (which does not exist in the actual file, along with the comments) are the values used each time to create the different arrangements. On the right there are comments about each parameter. Down to "value for cross connection" are the parameters used to describe stage 1. From that onwards are the parameters used in stage 2. As can be seen there are more parameters displayed than those used in the project as described in paragraphs "4.2.1.1" & "4.2.1.2". These are parameters that can be used for further investigation in the future. For each run, a different set of parameters was used and Index A of the resulting arrangement was calculated. The results were saved in a .CSV file for further examination. All the results from the various runs are displayed on appendices 1.1 & 1.2.

Chapter 5. Results

5.1. Stage 1

5.1.1. Number of bulkheads

The first series of runs were made using just transverse bulkheads. This outcome was to be used mostly as a benchmark. Increasing the number of bulkheads is the least that can be done on a ship to increase its safety. However compartmentation above a certain number is not possible due to manufacturing cost, excess weight and reduced functionality. As previously mentioned the number of bulkheads varied from 10 to 50 with a step of two. A representative sample of the ship's layout for this case is displayed below in figure 5.1.

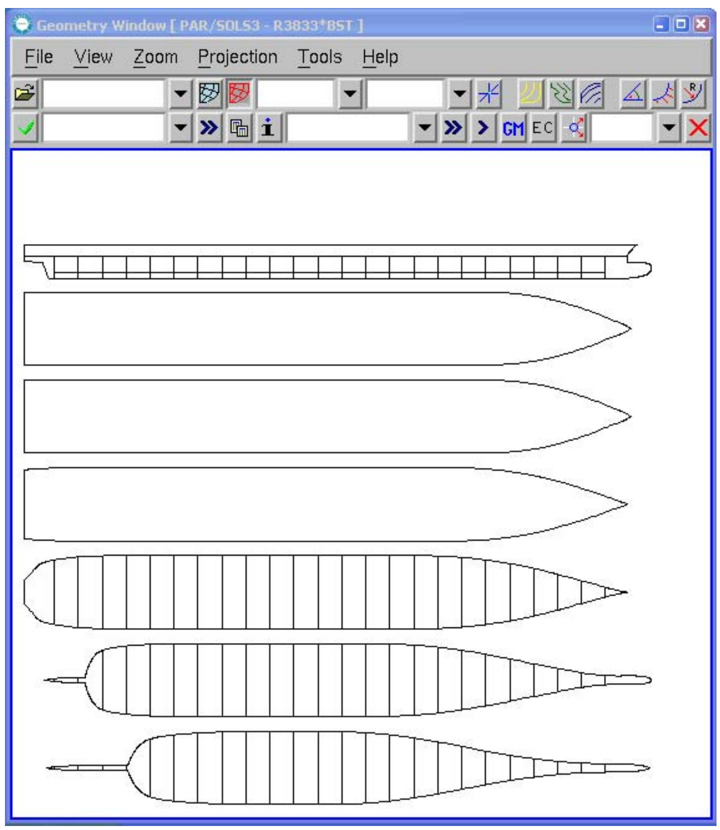
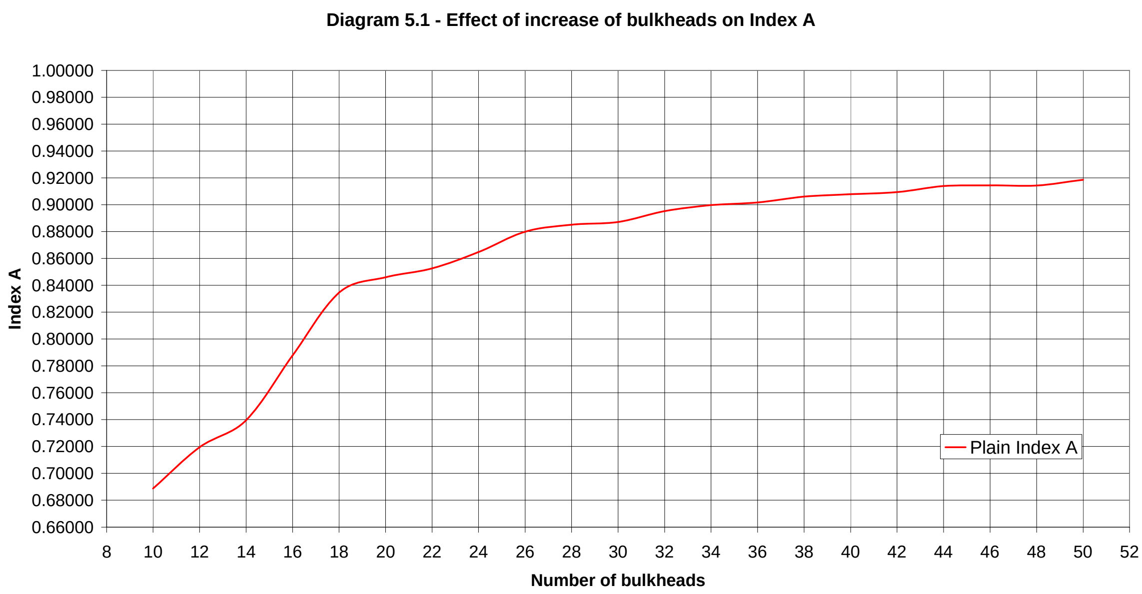


Figure 5.1
The model subdivided only longitudinally by 24 transverse bulkheads

Despite the initial expect that index A would exhibit a maximum at a specific number of bulkheads, this did not happen. On the contrary the plot of index A over number of bulkheads clearly demonstrated an asymptotic behaviour meaning that increasing the bulkheads it converges to a maximum value. Diagram 5.1 below shows the effect of the increase of bulkheads on Index A. It is quite clear that the graph is asymptotic to the value 0.92.



As shown on the chart, the maximum value in this case is approximately 0.92 @ 50 bulkheads. However the increase (dA) after 24-26 bulkheads is so insignificant that there seems to be no point in subdividing the ship more as the drawbacks are more than the benefits (cost, weight). Diagram 5.2 pictures the dA both in terms of A_{max} – A and A_{i+1} – A_i, where i is the number of bulkheads.

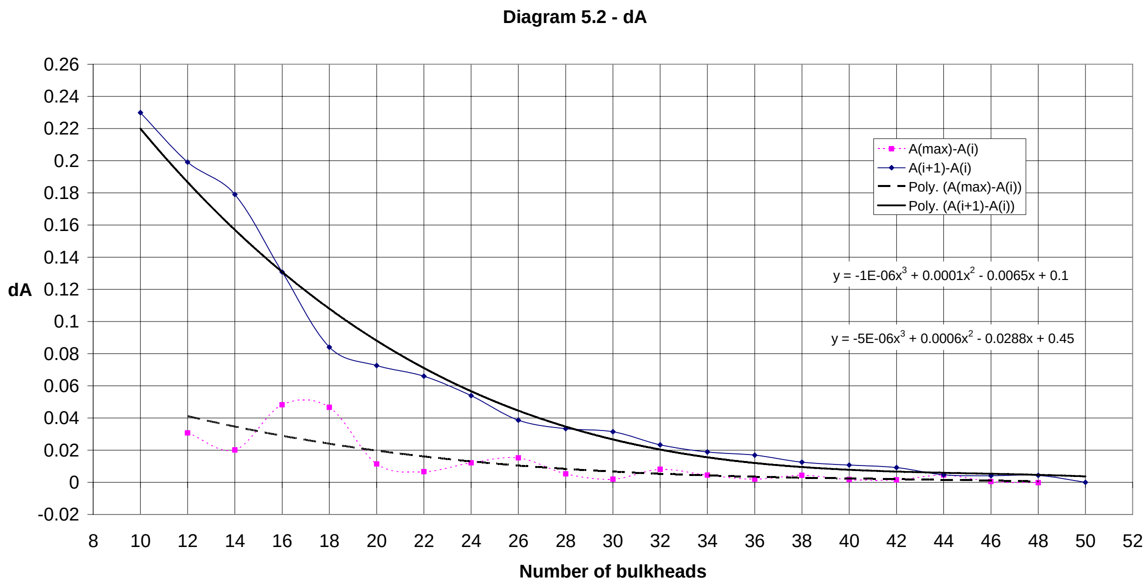
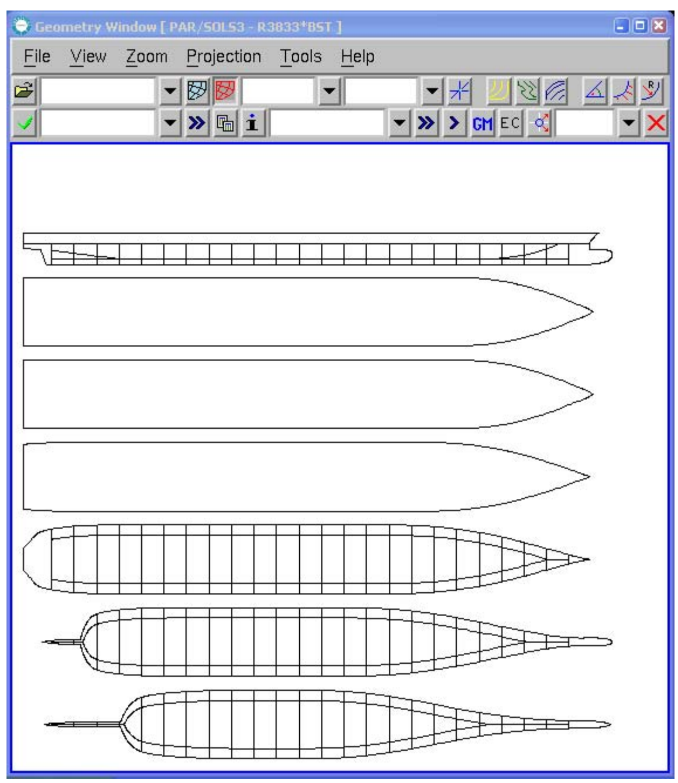


Diagram 5.2 - dA
dA
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
Number of bulkheads
A(max)-A(i)
A(i+1)-A(i)
Poly. (A(max)-A(i))
Poly. (A(i+1)-A(i))
y = -1E-06x3 + 0.0001x2 - 0.0065x + 0.1
y = -5E-06x3 + 0.0006x2 - 0.0288x + 0.45

5.1.2. Double hull

Double hull is considered to be one of the most beneficiary features a ship can display, in terms of damage safety. It was first instituted in the early nineties (right after the Exxon Valdez accident in Alaska) by the USA as an obligatory feature in crude oil tankers that were to operate in US water. Although other designs have been proposed as alternative approaches, such as the "coulombi egg" tanker based on Bernoulli's theorem of liquids, double hull is nowadays tending to be a necessity in almost any cargo ship. However it is not yet featured in passenger ships due to the complexity of building and difficulty in inspection. Its contribution though could not be neglected in this study since one of the first objectives is to cover most possible arrangements available. Barring the complexity, double hull can demonstrate huge benefit in safety. This of course stands only if portside and starboard tanks are cross connected. Otherwise survivability decreases dramatically due to asymmetrical flooding – leading to faster capsize. The parameter examined in the case of double hull is the clearance from the outer hull. Figure 5.2 demonstrates a representative example of the arrangement containing a double hull.

Figure 5.2
The model subdivided longitudinally by 24 transverse bulkheads and including a double hull with clearance of 0.15B from the outer hull



The various runs suggested that the result is an increase in Index A as clearance increased but as long as it was smaller than a quarter of the ships beam. That is because if the clearance is bigger than that, the flooded volume, including the cross connected opposite tank is bigger than the dry volume. In this case Index A is still greater than without the double hull but smaller than that achieved with smaller clearance (check diagram 5.4). Diagram 5.3 below shows the trends of Index A including double hull, plotted over the number of bulkheads. The trend of plain Index A has been added as a means of comparison, as well as the trend calculated without cross connection.

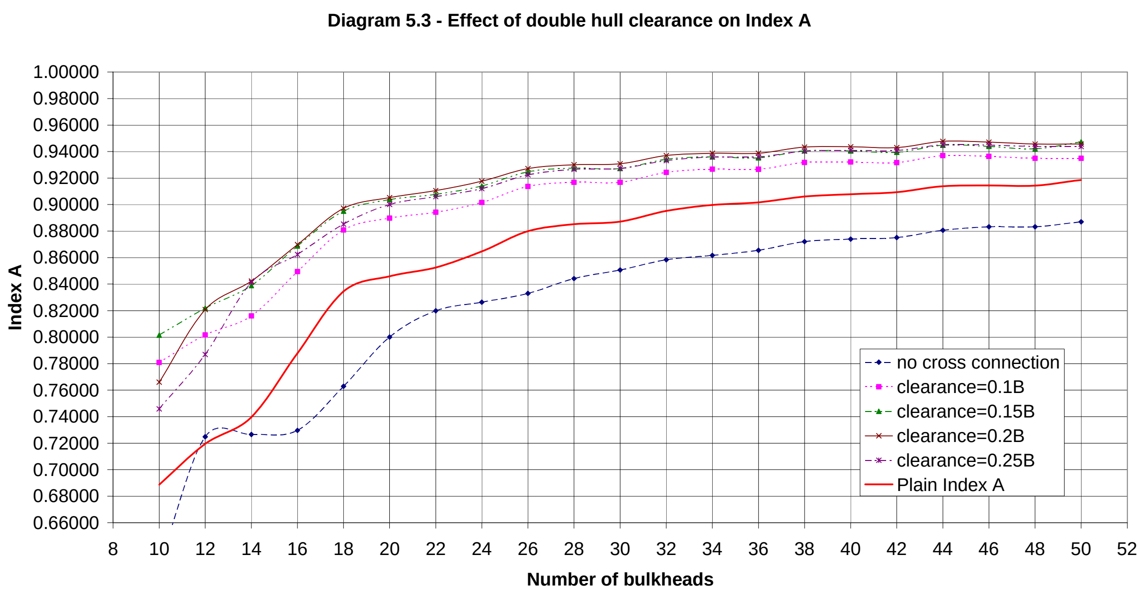
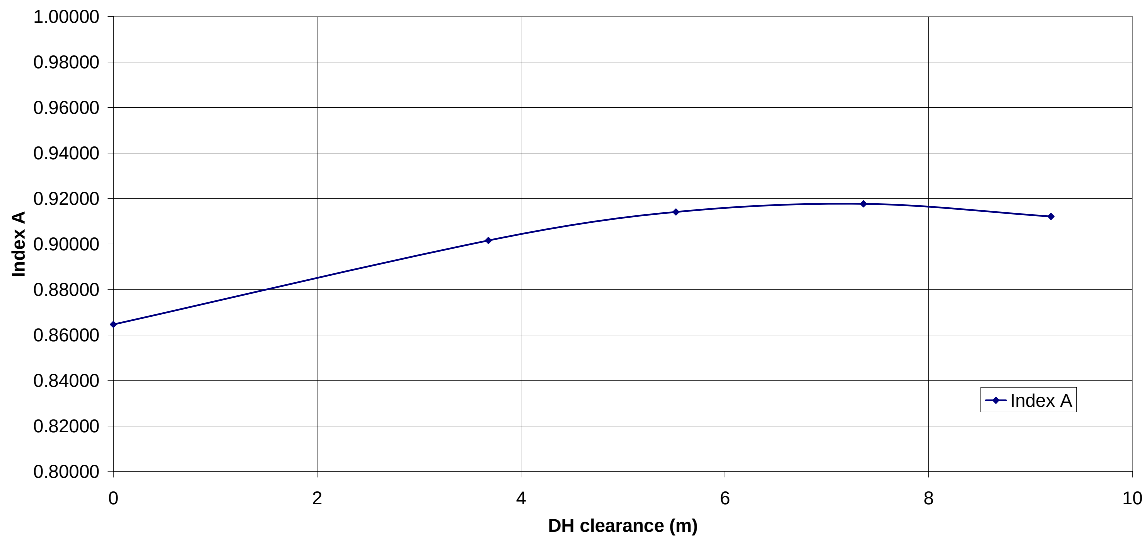


Diagram 5.4 below shows how Index A alters as the double hull clearance increases. The specimen values are for 24 bulkheads, which is near to the optimum value of bulkheads. It is clear that the maximum contribution is achieved with a clearance of the outer hull of 0.2B (7.36m) approximately. As mentioned before the contribution of the double hull might be decreasing for bigger values of clearance but it is still positive to the overall safety. After all if the clearance is bigger than a quarter of the ship's beam it is more likely to be considered as a central casing rather than a double hull. This is another case not covered by this study – maybe in the future, when it will be more common as a design feature.

Diagram 5.4 - Effect of double hull clearance on Index A @ 24 bulkheads



One other thing worth mentioning is that the double hull's contribution to the increase of Index A is the greater, the less the bulkheads. So by considering the double hull as a means of improving safety, or as an alternative means of reaching a required index, it is not necessary that the weight of the ship will be increased dramatically, since the number of bulkheads can be decreased a lot. For example, in the present case, in order to get Index A=0.9, one only needs 18 bulkheads and a double hull with 0.2B clearance, whereas more than 34 bulkheads would be needed without a double hull. A number that big would create such huge problems in the functionality of the ship that is more or less inapplicable.

Another positive outcome is that the clearance of the double hull is not a determinant factor for the increase of Index A. The presence alone of the double hull induces such improvement that one can actually use whatever value is best suited as long as it's less than 25% of the ships beam.

5.1.3. Deck raise

A deck raise in the form of a "step" in the fore, after or both parts of the main deck is also a quite common safety advancing feature in cargo ships as well as passenger ships. It is considered to be one easy way of increasing damage stability since the pitch angle is increased. In this study there has been examined an increase in both fore and after part together. The parameters used are the length of the raised deck and the height of the raise. Figure 5.3 demonstrates an example of an arrangement including a deck raise.

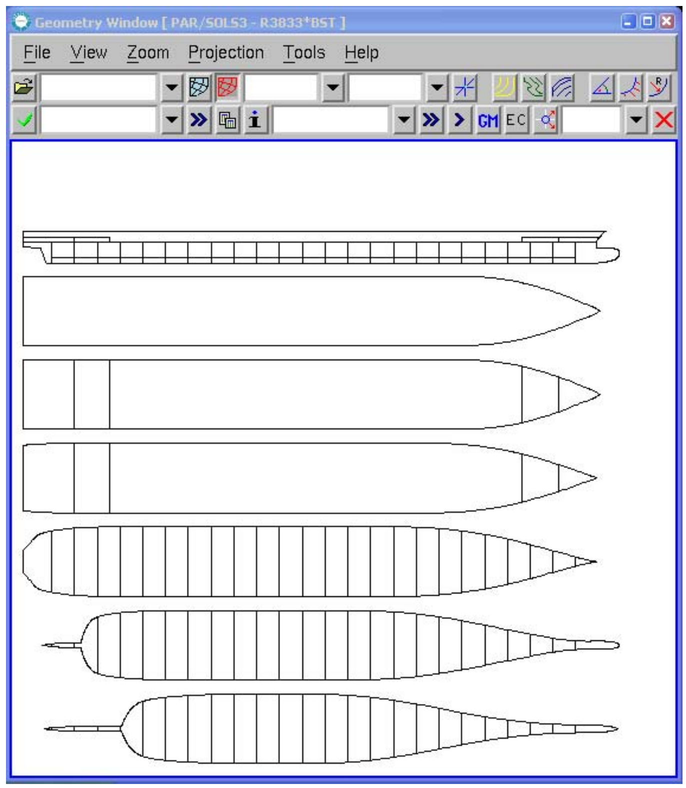


Figure 5.3
The model subdivided longitudinally by 24 transverse bulkheads and including a deck raise with length case 2 and height case 1

As can be seen in diagram 5.5, the raise seems to appear in two steps, each corresponding to a unit increase of the length. The affect of the raise in height is insignificant compared to that of increase of the length. It is clear from the proximity of the curves. The length of the deck raise plays a major role in the improvement of damage stability. On the other hand it is not so important to extend the watertight deck further on more than one deck. Another matter that arises from the observation of the chart is that unlike the double hull case the increase of Index A appears to be constant no matter what the number of bulkheads is and proportional to the length of the deck raise.

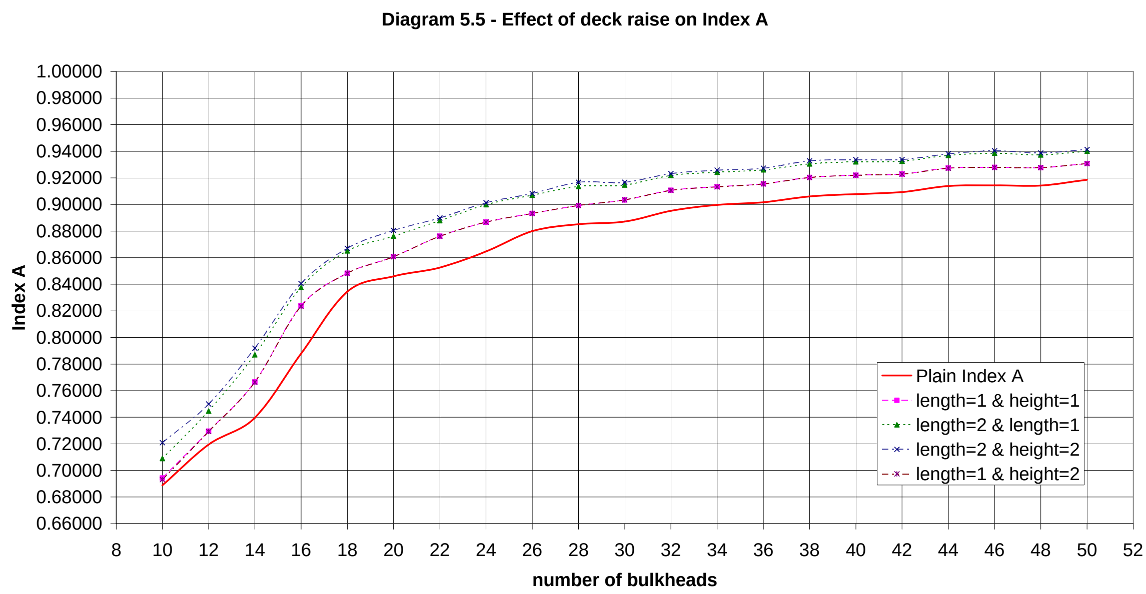
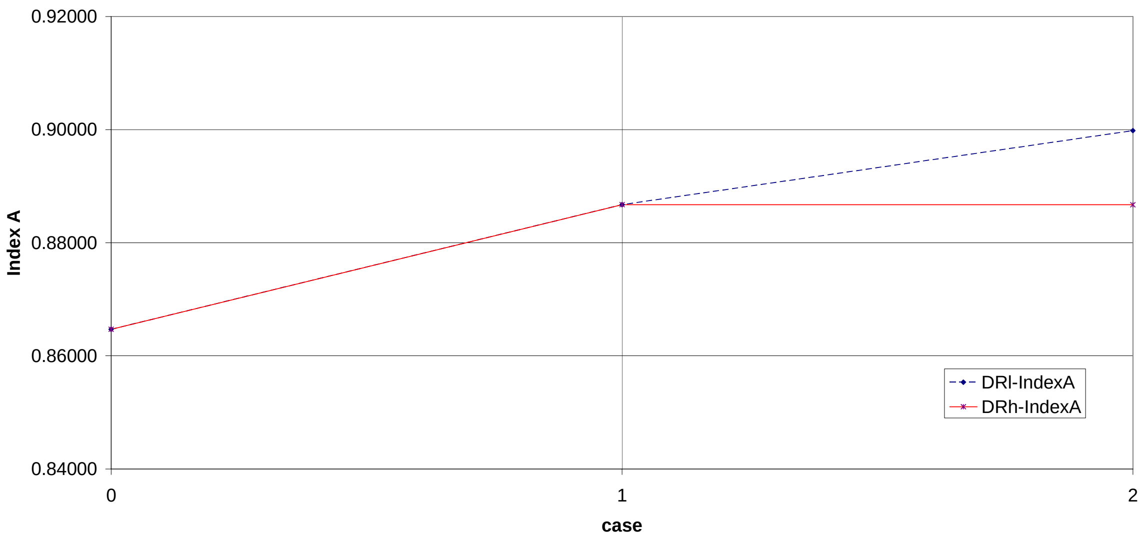


Diagram 5.6 demonstrates the increase of Index A in terms of length and height of the raised deck at 24 bulkheads. The first value is without deck raise. The second is the same for both cases since there can be no height without length and vice-versa, thus the cases are identical. The difference appears in the third value, where it is obvious that there is no increase in Index A as height increases. This chart also makes clearer that the increase of Index A as the length of the raised deck increases is almost linear.

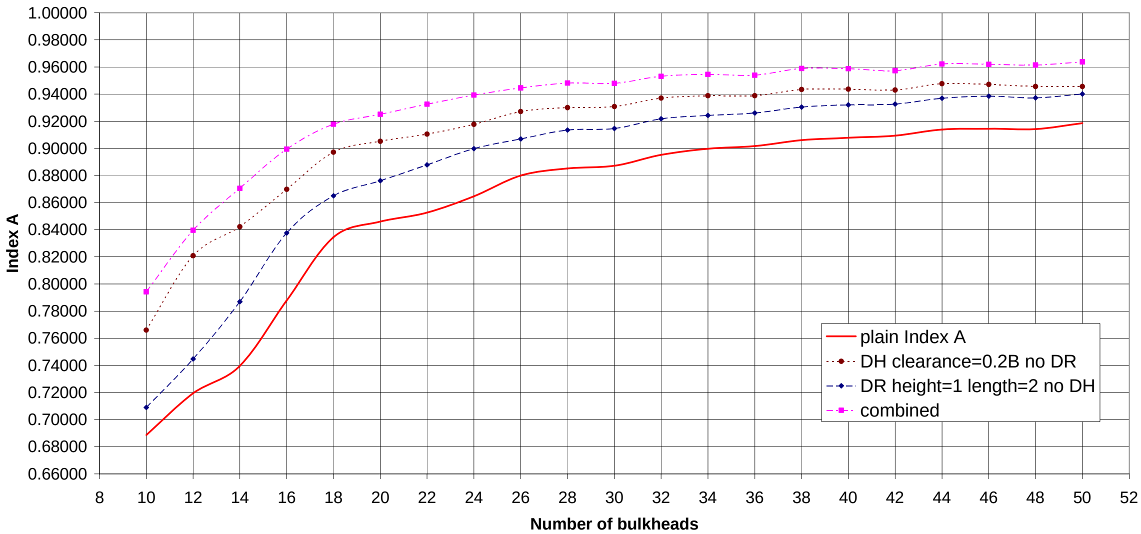
Diagram 5.6 - Effect of length and height of deck raise on Index A @ 24 bulkheads



5.1.4. Combined action of double hull and deck raise

More important than the isolated action of each one of the previous parameters is the effect they have if applied together. Various combinations could be done to test the outcome and they were done all. In none of them was there a drop in Index A. On the contrary every single combination seemed to be summing up the effect of the two parameters. In fact it is not exactly a sum but a big percentage of that, reaching 90% in most cases. For example diagram 5.7 that follows demonstrates the plain Index A, the optimum case for each one of the two aids (double hull and deck raise) and their combined action.

Diagram 5.7 - Increase of Index A under the combined action of DH clearance=0.2B and deck raise case 2-1



If taken for example the values for 24 bulkheads which is the optimum we have:

Case	Index A	Difference	Percentage of increase from plain	Percentage of combined action to adding separately
Plain	0.86469			
With DR	0.89982	+0.03513	+4.06%	
With DH	0.91770	+0.05301	+6.13%	
Combined	0.93929	+0.07460	+8.63%	84.64%

More diagrams can be found for further study in appendix 4

5.2. Stage 2

5.2.1. Side casings

One could describe the side casings as the life buoy of a ship. Their contribution is limited to extreme conditions only since the ship must sink a lot or undertake a great heel angle in order for the side casing to get underwater so it can contribute. It is in these extreme conditions though that the side casings' contribution can prove crucial. That is because side casings offer extra buoyancy where it is most needed. That is high and wide. Both resulting in an increased GM in case of flooding! However the current formula of **s** as is imposed by the rules ignores such high survivability measures. Figure 5.4 is a draft of what could be the GZ curve of a ship with side casings before and after damage.

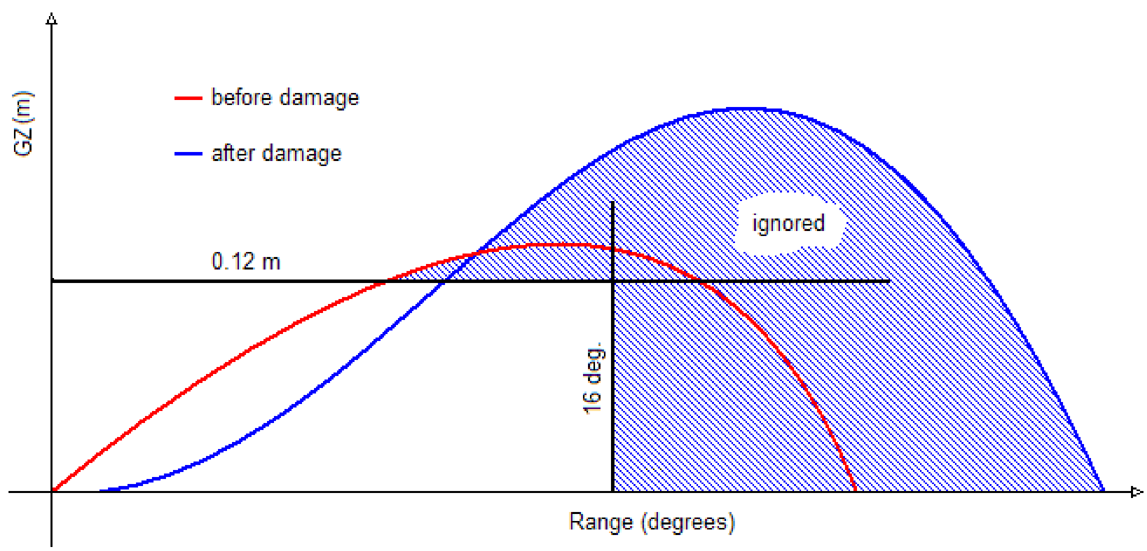


Figure 5.4

As it is shown in the figure, the stability limits literally leave out of the equation the benefit of the side casings. Nowhere is the above more obvious than in the results of the analysis but this shall be brought back to this after the results have been presented. Figure 5.5 & 5.6 demonstrate the ship's arrangement with side casings.

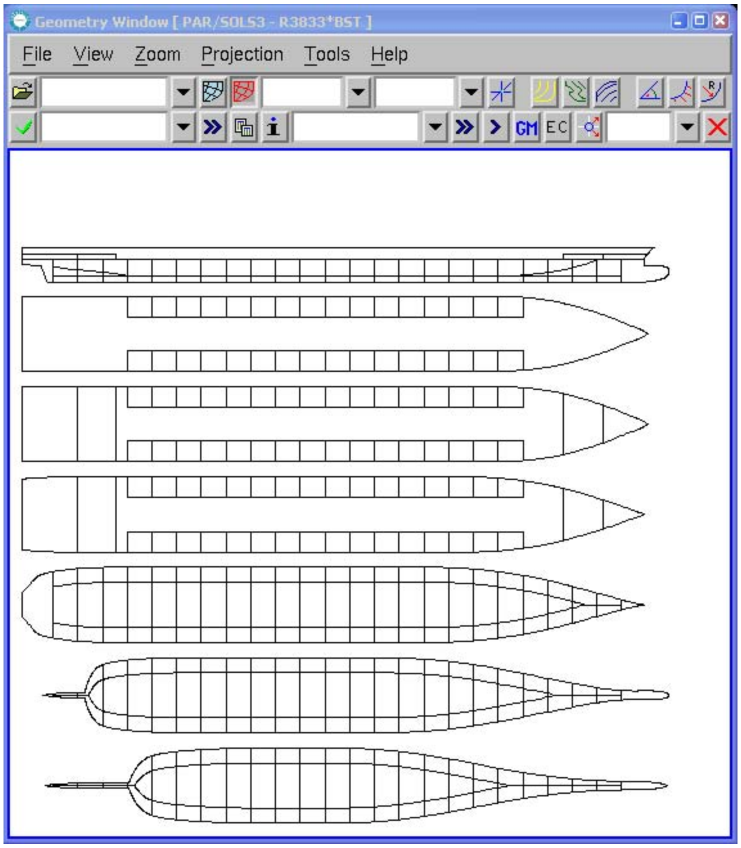


Figure 5.5

Side casing subdivided above every bulkhead

The model subdivided longitudinally by 24 transverse bulkheads, including a deck raise and double hull as well as side casings

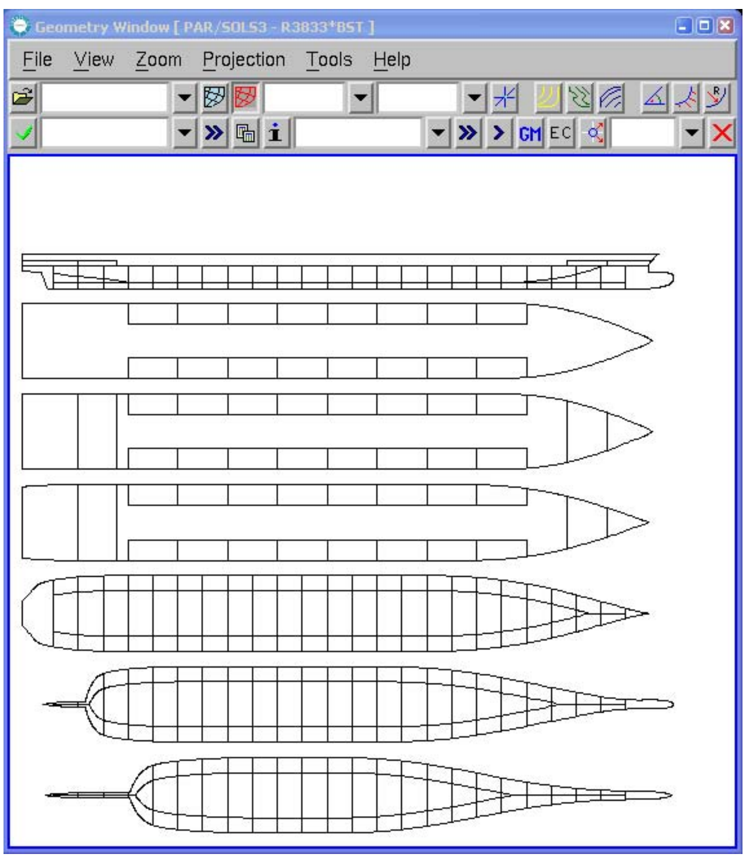
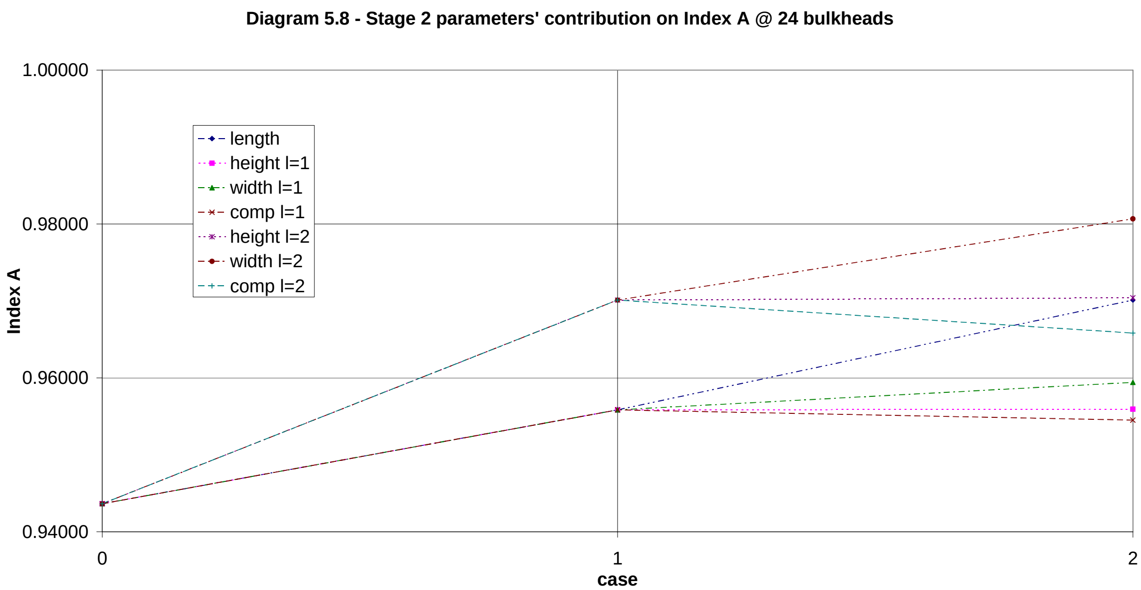


Figure 5.6

Side casing subdivided above every other bulkhead

The parameters used to describe the side casings are their length, height, width and compartmentation. The length of the side casings is set to have two values: 33% and 66% of the ship's length approximately, which are named as case 1 and 2 respectively. The width is either five or ten meters, again named case 1 or 2. The height is either one or two decks above the bulkhead deck and finally the side casings were subdivided either every one or every two bulkheads below them, leading to 1 or 2 compartment spaces. Both layouts in figures 5.5 and 5.6 have side casings that extend to 66% of the ship's length, are of 10 m width and 2 deck height but arrangement 5.5 has tighter compartmentation than 5.6. The contribution of compartmentation is of great importance since the space where side casings are placed is mainly passenger space and any excess of barriers is a serious drawback.

The arrangement used from stage 1 to build upon it stage 2 is that which has a double hull with clearance 0.2B, a deck raise with length 2 and height 1 and 24 transverse bulkheads, which demonstrated the highest survivability. This seems to be the optimum from the point of view of manufacturing simplicity, economy and safety. A simpler arrangement could have been used but since one of this project's objectives is optimization, it was considered wise to use the optimum arrangement. Diagram 5.8 below shows several trends of Index A plotted at 24 bulkheads and for the various values of the parameters.



From the above diagram it is obvious that the length of the side casings has the largest contribution on Index A. The lower curves are of length case 1 while the above are for length case 2. What can be observed is the slight deduction made by sparser compartmentation. In fact it is so negligible that it can even be safely said that such tight compartmentation is unnecessary considering the huge benefits. Width also contributes less than length but what is really remarkable is that height doesn't contribute at all whatsoever! Such an outcome is certainly against any common sense and is entirely attributed to the incompetence of the calculation to include such high survivability measures. The only way there is to prove that raising the height of the side casing does indeed increase safety is by numerical simulation. Nevertheless a revision of the formulae of probabilistic damage assessment would be advisable mostly considering that these were derived from studies on Ro-Ro's and could be quite different for any other type of ship.

More diagrams can be found for further study in appendix 4

5.2.2. Partial bulkheads

Unfortunately some problems with the arrangements needed for the evaluation of safety with the contribution of partial bulkheads couldn't be resolved up to the end so I decided to leave it for the future since the need for the degree was immense. This is really a pity since if their contribution proved to be at least equal to that of the side casings it would resolve many of the problems caused by the watertight longitudinal bulkhead of the later. However NAPA seemed unable to create compartments without at least 6 faces or at least I was unable to do it. Nevertheless their contribution has to be put to the test and it shall be done along with some other features that might as well benefit damage stability.

6. Optimization

6.1. Multiple regression

Since this study is ultimately an optimization process it could not be complete without an equation of Index A and the variables. With this equation one can set a goal, for example A=0.99 and see what options there are of combinations of the parameters in order to achieve that. This process is also necessary so that a weighting factor for each parameter is calculated. This process is called multiple regression and is described by the following example. The general purpose of multiple regression (the term was first used by Pearson, 1908) is to learn more about the relationship between several independent or predictor variables and a dependent or criterion variable. For example, a real estate agent might record for each listing the size of the house (in square feet), the number of bedrooms, the average income in the respective neighbourhood according to census data, and a subjective rating of appeal of the house. Once this information has been compiled for various houses it would be interesting to see whether and how these measures relate to the price for which a house is sold. For example, one might learn that the number of bedrooms is a better predictor of the price for which a house sells in a particular neighbourhood than how "pretty" the house is (subjective rating). One may also detect "outliers," that is, houses that should really sell for more, given their location and characteristics. In our case the price of the house is Index A with the various parameters as described in previous chapter.

There are a lot of multiple regression tools over the internet, however from my search I ended up using Vassar Stats multiple regression tool [8] since it’s one of the easiest and more complete there could be found. The layout of the tool is so simple that even data from excel spreadsheets can be used identically. Then the only thing left to do is set the parameters and run the tool. The software comes up with the multiple regression equation which is of the general form:

$$Y = a + b_1X_1 + b_2X_2 + \cdots + b_kX_k$$

where **a** is a starting-point constant analogous to the intercept in a simple two-variable regression, and $\mathbf{b_1}$, $\mathbf{b_2}$, etc., are the unstandardized regression weights for X_1, X_2, etc., each analogous to the slope in a simple two-variable regression.

6.2. Multiple regression for stage 1

In the present analysis, **a** = 0.6791 and the values of **b** are as indicated below. The values listed as **B** in table 6.1 are the standardized regression weights.

		b	**B**	**B x r_{xy}**
number of BHDs	**X1**	0.0035	0.7412	0.5494
double hull clearance	**X2**	0.0045	0.2471	0.0672
deck raise length	**X3**	0.0107	0.1409	0.0109
deck raise height	**X4**	0.0012	0.0104	0.0011
cross connection	**X5**	0.0895	0.3018	0.0897
Multiple $\mathbf{R^2}$ = 0.7181				
Adjusted Multiple $\mathbf{R^2}$ = 0.7155				
Standard Error of Multiple Estimate = 0.0303				

Table 6.1

So the equation is:

$$A = 0.6791 + 0.0035x_1 + 0.0045x_2 + 0.0107x_3 + 0.0012x_4 + 0.0895x_5$$

The correlation matrix is:

	X1	**X2**	**X3**	**X4**	**X5**	**Y**
X1	**1**	0	0	0	0	0.741
X2	0	**1**	-0.019	0.014	0.1	0.272
X3	0	-0.019	**1**	0.284	-0	0.077
X4	0	0.014	0.284	**1**	0.2	0.101
X5	0	0.091	-0.205	0.159	**1**	0.297
Y	0.741	0.272	0.077	0.101	0.3	**1**

Table 6.2

As can be seen from the standardized regression weights (table 6.1, 'B' values) the most important influence on Index A has the number of bulkheads. Second in importance appears to be the clearance of the double hull by approximately 3 times. Third is the length of the raised deck by six times and last the raised deck height by more than ten times from bulkheads. Of course cross connection is very important too but this is not exactly a parameter since it's got two values only. The fact that all the unstandardized regression weights are positive shows that every single parameter's contribution is additive.

6.3. Multiple regression for stage 2

As stated before in the second stage an optimum design below subdivision deck has been used so as expected value **a** is increased compared to stage 1. According to the process the values of the various parameters as well as their weighting factors are shown in the following table.

		b	**B**	**B x r_{xy}**
Number of BHDs	**X1**	0.0019	0.2692	0.0725
SClength(*L)	**X2**	0.0576	0.8412	0.7077
SCheight(decks)	**X3**	-0.0017	-0.0758	0.0058
SCwidth(m)	**X4**	0.0011	0.2308	0.0532
SCcomp.	**X5**	-0.0039	-0.173	0.0299
Multiple $\mathbf{R}^2$ = 0.869				
Adjusted Multiple $\mathbf{R}^2$ = 0.8534				
Standard Error of Multiple Estimate = 0.0042				

Table 6.3

The regression equation that resulted from this process is:

$$A = 0.89210 + 0.00190x_1 + 0.05760x_2 - 0.00170x_3 + 0.00110x_4 - 0.00390x_5$$

Once again it is quite obvious that the most important parameter is with no doubt the length of the side casings with everything else following by more than 10 times less importance. What seemed at first a computational error is the fact that the height of the side casings reduces marginally the attained index. As it turned out it is not one. The real meaning of that paradox, according to common sense, is that the calculation formula of index A is inadequate when it comes to high survivability measures. The extra stability offered by the extension of the side casings to more than one decks above subdivision deck is cut out from the limits used in the formulation.

The next step is to run all the arrangements in simulation programs such as PROTEUS® in order to check if what we call common sense proves itself right. If that is the case then we can be sure that there are some changes that need to be made to the formulation of index A in order to include all the different high survivability measures.

Chapter 9. Conclusion

The study of ship damage stability seems endless as endless seem the alterations in ship general arrangements. Today is yesterday's future as a philosopher might say, meaning that nothing can ever stop progress. However progress can sometimes be leaping forward and other times standing seemingly still for decades or centuries. Even so on periods of stillness though, progress is made in the form of the maturing of ideas in humanities minds. Some things are far too difficult for the human brain to accept (say probability) so other kind of progress has to be done in order for certain ideas to come forward again.

Such is the case with probabilistic approach in damage stability. Whatsoever it seems that once it has began, probabilistic approach will extend to almost every aspect of our lives. As for damage stability, it has been evolving rapidly during the last few years. Naval architects are entering fields where few have been before and all the help one can get is welcome. Index A has just started to unveil its massive importance although still a little rough around the edges. For example why should a formulation that resulted from the study in one type of ships be applied to all? Its weaknesses are more than obvious in certain cases such as the side casings' height for example that seems to be reducing safety, a conclusion totally obscure.

Hereupon index A seems to be affected more by changes in the arrangement below subdivision deck rather than above it. This is because of the values in the GZ curve and Range that limit the formulation of A. Among them the number of bulkheads is undoubtedly the number one parameter a designer must increase in order to obtain maximum safety. This is not new knowledge but what is new is that index A won't increase sine die. Its increase becomes insignificant after a compartmentation length greater than 5.5% of L (see diagram 5, appendix 4). Double hull also contributes a lot especially the lesser the bulkheads which means it can be used as an alternative feature other than bulkheads in cases where small compartmentation is unwanted. Other than that deck raise is unnecessary to extend to more than one deck above subdivision deck but its length should be the maximum possible.

As for the extension of the watertight envelope above subdivision deck it definitely contributes although its contribution is partly unveiled. The appearance and only of side casings whatever their extent is enough to increase index A by 1.3% at least and can reach up to 4.1% with tight compartmentation and sound length and width.

However, high survivability measures such as side casings require extreme conditions to demonstrate their contribution and index A formulation leaves extreme conditions out of the equation lying on the safe side, or at least believing to do so. The problem is that by not knowing how much damage stability is affected or if it is affected at all we are in danger of entering once again in the dangerous territory of prescriptive regulations. Designers must know if their efforts pay or they might not even get in the trouble.

We dream of a future where all ships will be “mistake proof” and absolutely free of any kind of risk. Although there is still a long way to be covered towards this direction very important steps have been made. Ships already being built are safer by a magnitude than their predecessors making us think that anything is possible.

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Appendices

Appendix 1. Analytical results

1.1. Stage 1

# of BHDs	DH clear.	DR length	DR height	Comp. vol.	**Index A**
10	0	0	1	7706.42	**0.68873**
12	0	0	1	6305.25	**0.71946**
14	0	0	1	5335.21	**0.73961**
16	0	0	1	4623.85	**0.78783**
18	0	0	1	4079.87	**0.83451**
20	0	0	1	3650.41	**0.84595**
22	0	0	1	3302.75	**0.85258**
24	0	0	1	3015.55	**0.86469**
26	0	0	1	2774.31	**0.87991**
28	0	0	1	2568.81	**0.88518**
30	0	0	1	2391.65	**0.88713**
32	0	0	1	2237.35	**0.89521**
34	0	0	1	2101.75	**0.89971**
36	0	0	1	1981.65	**0.90167**
38	0	0	1	1874.53	**0.90605**
40	0	0	1	1778.40	**0.90781**
42	0	0	1	1691.65	**0.90936**
44	0	0	1	1612.97	**0.91391**
46	0	0	1	1541.28	**0.91444**
48	0	0	1	1475.70	**0.91427**
50	0	0	1	1415.46	**0.91858**
10	0	1	1	7706.42	**0.69432**
12	0	1	1	6305.25	**0.72946**
14	0	1	1	5335.21	**0.76657**
16	0	1	1	4623.85	**0.82382**
18	0	1	1	4079.87	**0.84829**
20	0	1	1	3650.41	**0.86078**
22	0	1	1	3302.75	**0.87615**
24	0	1	1	3015.55	**0.88673**
26	0	1	1	2774.31	**0.89328**
28	0	1	1	2568.81	**0.89923**
30	0	1	1	2391.65	**0.90339**
32	0	1	1	2237.35	**0.91065**
34	0	1	1	2101.75	**0.91340**
36	0	1	1	1981.65	**0.91559**
38	0	1	1	1874.53	**0.92039**
40	0	1	1	1778.40	**0.92203**

42	0	1	1	1691.65	**0.92289**
44	0	1	1	1612.97	**0.92744**
46	0	1	1	1541.28	**0.92793**
48	0	1	1	1475.70	**0.92774**
50	0	1	1	1415.46	**0.93079**
10	0	2	1	7706.42	**0.70893**
12	0	2	1	6305.25	**0.74472**
14	0	2	1	5335.21	**0.78697**
16	0	2	1	4623.85	**0.83761**
18	0	2	1	4079.87	**0.86506**
20	0	2	1	3650.41	**0.87613**
22	0	2	1	3302.75	**0.88781**
24	0	2	1	3015.55	**0.89982**
26	0	2	1	2774.31	**0.90696**
28	0	2	1	2568.81	**0.91354**
30	0	2	1	2391.65	**0.91467**
32	0	2	1	2237.35	**0.92180**
34	0	2	1	2101.75	**0.92431**
36	0	2	1	1981.65	**0.92607**
38	0	2	1	1874.53	**0.93048**
40	0	2	1	1778.40	**0.93207**
42	0	2	1	1691.65	**0.93261**
44	0	2	1	1612.97	**0.93694**
46	0	2	1	1541.28	**0.93850**
48	0	2	1	1475.70	**0.93726**
50	0	2	1	1415.46	**0.94010**
10	0	2	2	7706.42	**0.72087**
12	0	2	2	6305.25	**0.74987**
14	0	2	2	5335.21	**0.79193**
16	0	2	2	4623.85	**0.84055**
18	0	2	2	4079.87	**0.86705**
20	0	2	2	3650.41	**0.88049**
22	0	2	2	3302.75	**0.88989**
24	0	2	2	3015.55	**0.90135**
26	0	2	2	2774.31	**0.90826**
28	0	2	2	2568.81	**0.91669**
30	0	2	2	2391.65	**0.91668**
32	0	2	2	2237.35	**0.92324**
34	0	2	2	2101.75	**0.92577**
36	0	2	2	1981.65	**0.92726**
38	0	2	2	1874.53	**0.93281**
40	0	2	2	1778.40	**0.93372**
42	0	2	2	1691.65	**0.93384**
44	0	2	2	1612.97	**0.93812**
46	0	2	2	1541.28	**0.94042**
48	0	2	2	1475.70	**0.93879**
50	0	2	2	1415.46	**0.94139**
10	0	1	2	7706.42	**0.69303**

12	0	1	2	6305.25	**0.72920**
14	0	1	2	5335.21	**0.76636**
16	0	1	2	4623.85	**0.82341**
18	0	1	2	4079.87	**0.84821**
20	0	1	2	3650.41	**0.86062**
22	0	1	2	3302.75	**0.87607**
24	0	1	2	3015.55	**0.88672**
26	0	1	2	2774.31	**0.89329**
28	0	1	2	2568.81	**0.89930**
30	0	1	2	2391.65	**0.90346**
32	0	1	2	2237.35	**0.91064**
34	0	1	2	2101.75	**0.91326**
36	0	1	2	1981.65	**0.91550**
38	0	1	2	1874.53	**0.92028**
40	0	1	2	1778.40	**0.92197**
42	0	1	2	1691.65	**0.92285**
44	0	1	2	1612.97	**0.92732**
46	0	1	2	1541.28	**0.92790**
48	0	1	2	1475.70	**0.92775**
50	0	1	2	1415.46	**0.93079**
10	3.68	0	1	7706.42	**0.78088**
12	3.68	0	1	6305.25	**0.80166**
14	3.68	0	1	5335.21	**0.81595**
16	3.68	0	1	4623.85	**0.84944**
18	3.68	0	1	4079.87	**0.88088**
20	3.68	0	1	3650.41	**0.88979**
22	3.68	0	1	3302.75	**0.89420**
24	3.68	0	1	3015.55	**0.90158**
26	3.68	0	1	2774.31	**0.91374**
28	3.68	0	1	2568.81	**0.91689**
30	3.68	0	1	2391.65	**0.91690**
32	3.68	0	1	2237.35	**0.92435**
34	3.68	0	1	2101.75	**0.92674**
36	3.68	0	1	1981.65	**0.92663**
38	3.68	0	1	1874.53	**0.93180**
40	3.68	0	1	1778.40	**0.93210**
42	3.68	0	1	1691.65	**0.93170**
44	3.68	0	1	1612.97	**0.93693**
46	3.68	0	1	1541.28	**0.93636**
48	3.68	0	1	1475.70	**0.93497**
50	3.68	0	1	1415.46	**0.93497**
10	3.68	1	1	7706.42	**0.78594**
12	3.68	1	1	6305.25	**0.80978**
14	3.68	1	1	5335.21	**0.83580**
16	3.68	1	1	4623.85	**0.87549**
18	3.68	1	1	4079.87	**0.89142**
20	3.68	1	1	3650.41	**0.90106**
22	3.68	1	1	3302.75	**0.91155**

24	3.68	1	1	3015.55	**0.91782**
28	3.68	1	1	2568.81	**0.92745**
30	3.68	1	1	2391.65	**0.92901**
32	3.68	1	1	2237.35	**0.93589**
34	3.68	1	1	2101.75	**0.93704**
36	3.68	1	1	1981.65	**0.93706**
38	3.68	1	1	1874.53	**0.94254**
40	3.68	1	1	1778.40	**0.94273**
42	3.68	1	1	1691.65	**0.94183**
44	3.68	1	1	1612.97	**0.94709**
46	3.68	1	1	1541.28	**0.94648**
48	3.68	1	1	1475.70	**0.94506**
50	3.68	1	1	1415.46	**0.94914**
10	3.68	2	1	7706.42	**0.79632**
12	3.68	2	1	6305.25	**0.82094**
14	3.68	2	1	5335.21	**0.85048**
16	3.68	2	1	4623.85	**0.88551**
18	3.68	2	1	4079.87	**0.90359**
20	3.68	2	1	3650.41	**0.91224**
22	3.68	2	1	3302.75	**0.92015**
24	3.68	2	1	3015.55	**0.92740**
26	3.68	2	1	2774.31	**0.93381**
28	3.68	2	1	2568.81	**0.93788**
30	3.68	2	1	2391.65	**0.93728**
32	3.68	2	1	2237.35	**0.94410**
34	3.68	2	1	2101.75	**0.94507**
36	3.68	2	1	1981.65	**0.94477**
38	3.68	2	1	1874.53	**0.94998**
40	3.68	2	1	1778.40	**0.95013**
42	3.68	2	1	1691.65	**0.94899**
44	3.68	2	1	1612.97	**0.95410**
46	3.68	2	1	1541.28	**0.95424**
48	3.68	2	1	1475.70	**0.95206**
50	3.68	2	1	1415.46	**0.95600**
10	3.68	2	2	7706.42	**0.80396**
12	3.68	2	2	6305.25	**0.82455**
14	3.68	2	2	5335.21	**0.85399**
16	3.68	2	2	4623.85	**0.88759**
18	3.68	2	2	4079.87	**0.90514**
20	3.68	2	2	3650.41	**0.91534**
22	3.68	2	2	3302.75	**0.92166**
24	3.68	2	2	3015.55	**0.92852**
26	3.68	2	2	2774.31	**0.93475**
28	3.68	2	2	2568.81	**0.94013**
30	3.68	2	2	2391.65	**0.93873**
32	3.68	2	2	2237.35	**0.94514**
34	3.68	2	2	2101.75	**0.94612**
36	3.68	2	2	1981.65	**0.94563**

38	3.68	2	2	1874.53	**0.95170**
40	3.68	2	2	1778.40	**0.95133**
42	3.68	2	2	1691.65	**0.94989**
44	3.68	2	2	1612.97	**0.95510**
46	3.68	2	2	1541.28	**0.95476**
48	3.68	2	2	1475.70	**0.95317**
50	3.68	2	2	1415.46	**0.95694**
10	3.68	1	2	7706.42	**0.78502**
12	3.68	1	2	6305.25	**0.80959**
14	3.68	1	2	5335.21	**0.83564**
16	3.68	1	2	4623.85	**0.87520**
18	3.68	1	2	4079.87	**0.89136**
20	3.68	1	2	3650.41	**0.90095**
22	3.68	1	2	3302.75	**0.91149**
24	3.68	1	2	3015.55	**0.91782**
26	3.68	1	2	2774.31	**0.92384**
28	3.68	1	2	2568.81	**0.92751**
30	3.68	1	2	2391.65	**0.92907**
32	3.68	1	2	2237.35	**0.93589**
34	3.68	1	2	2101.75	**0.93694**
36	3.68	1	2	1981.65	**0.93700**
38	3.68	1	2	1874.53	**0.94246**
40	3.68	1	2	1778.40	**0.94269**
42	3.68	1	2	1691.65	**0.94181**
44	3.68	1	2	1612.97	**0.94700**
46	3.68	1	2	1541.28	**0.94675**
48	3.68	1	2	1475.70	**0.94506**
50	3.68	1	2	1415.46	**0.94915**
10	5.52	0	1	7706.42	**0.80158**
12	5.52	0	1	6305.25	**0.82181**
14	5.52	0	1	5335.21	**0.83887**
16	5.52	0	1	4623.85	**0.86876**
18	5.52	0	1	4079.87	**0.89502**
20	5.52	0	1	3650.41	**0.90377**
22	5.52	0	1	3302.75	**0.90774**
24	5.52	0	1	3015.55	**0.91407**
26	5.52	0	1	2774.31	**0.92474**
28	5.52	0	1	2568.81	**0.92748**
30	5.52	0	1	2391.65	**0.92723**
32	5.52	0	1	2237.35	**0.93419**
34	5.52	0	1	2101.75	**0.93605**
36	5.52	0	1	1981.65	**0.93529**
38	5.52	0	1	1874.53	**0.94061**
40	5.52	0	1	1778.40	**0.94050**
42	5.52	0	1	1691.65	**0.93942**
44	5.52	0	1	1612.97	**0.94486**
46	5.52	0	1	1541.28	**0.94393**
48	5.52	0	1	1475.70	**0.94212**

50	5.52	0	1	1415.46	**0.94729**
10	5.52	1	1	7706.42	**0.80723**
12	5.52	1	1	6305.25	**0.83059**
14	5.52	1	1	5335.21	**0.85689**
16	5.52	1	1	4623.85	**0.89130**
18	5.52	1	1	4079.87	**0.90505**
20	5.52	1	1	3650.41	**0.91426**
22	5.52	1	1	3302.75	**0.92321**
24	5.52	1	1	3015.55	**0.92847**
26	5.52	1	1	2774.31	**0.93403**
28	5.52	1	1	2568.81	**0.93704**
30	5.52	1	1	2391.65	**0.93796**
32	5.52	1	1	2237.35	**0.94450**
34	5.52	1	1	2101.75	**0.94528**
36	5.52	1	1	1981.65	**0.94461**
38	5.52	1	1	1874.53	**0.95021**
40	5.52	1	1	1778.40	**0.94999**
42	5.52	1	1	1691.65	**0.94848**
44	5.52	1	1	1612.97	**0.95394**
46	5.52	1	1	1541.28	**0.95296**
48	5.52	1	1	1475.70	**0.95183**
50	5.52	1	1	1415.46	**0.95555**
10	5.52	2	1	7706.42	**0.81747**
12	5.52	2	1	6305.25	**0.84046**
14	5.52	2	1	5335.21	**0.86978**
16	5.52	2	1	4623.85	**0.90041**
18	5.52	2	1	4079.87	**0.91580**
20	5.52	2	1	3650.41	**0.92413**
22	5.52	2	1	3302.75	**0.93091**
24	5.52	2	1	3015.55	**0.93696**
26	5.52	2	1	2774.31	**0.94287**
28	5.52	2	1	2568.81	**0.94628**
30	5.52	2	1	2391.65	**0.94537**
32	5.52	2	1	2237.35	**0.95183**
34	5.52	2	1	2101.75	**0.95241**
36	5.52	2	1	1981.65	**0.95104**
38	5.52	2	1	1874.53	**0.95683**
40	5.52	2	1	1778.40	**0.95656**
42	5.52	2	1	1691.65	**0.95484**
44	5.52	2	1	1612.97	**0.96019**
46	5.52	2	1	1541.28	**0.95983**
48	5.52	2	1	1475.70	**0.95733**
50	5.52	2	1	1415.46	**0.96166**
10	5.52	2	2	7706.42	**0.82390**
12	5.52	2	2	6305.25	**0.84365**
14	5.52	2	2	5335.21	**0.87283**

16	5.52	2	2	4623.85	**0.90216**
18	5.52	2	2	4079.87	**0.91704**
20	5.52	2	2	3650.41	**0.92679**
22	5.52	2	2	3302.75	**0.93160**
24	5.52	2	2	3015.55	**0.93795**
26	5.52	2	2	2774.31	**0.94369**
28	5.52	2	2	2568.81	**0.94821**
30	5.52	2	2	2391.65	**0.94663**
32	5.52	2	2	2237.35	**0.95275**
34	5.52	2	2	2101.75	**0.95335**
36	5.52	2	2	1981.65	**0.95221**
38	5.52	2	2	1874.53	**0.95828**
40	5.52	2	2	1778.40	**0.95761**
42	5.52	2	2	1691.65	**0.95654**
44	5.52	2	2	1612.97	**0.96081**
46	5.52	2	2	1541.28	**0.96104**
48	5.52	2	2	1475.70	**0.95892**
50	5.52	2	2	1415.46	**0.96321**
10	5.52	1	2	7706.42	**0.80653**
12	5.52	1	2	6305.25	**0.83044**
14	5.52	1	2	5335.21	**0.85673**
16	5.52	1	2	4623.85	**0.89105**
18	5.52	1	2	4079.87	**0.90499**
20	5.52	1	2	3650.41	**0.91415**
22	5.52	1	2	3302.75	**0.92314**
24	5.52	1	2	3015.55	**0.92845**
26	5.52	1	2	2774.31	**0.93404**
28	5.52	1	2	2568.81	**0.93709**
30	5.52	1	2	2391.65	**0.93800**
32	5.52	1	2	2237.35	**0.94450**
34	5.52	1	2	2101.75	**0.94519**
36	5.52	1	2	1981.65	**0.94455**
38	5.52	1	2	1874.53	**0.95014**
40	5.52	1	2	1778.40	**0.94995**
42	5.52	1	2	1691.65	**0.94845**
44	5.52	1	2	1612.97	**0.95386**
46	5.52	1	2	1541.28	**0.95294**
48	5.52	1	2	1475.70	**0.95111**
50	5.52	1	2	1415.46	**0.95555**
10	7.36	0	1	7706.42	**0.76606**
12	7.36	0	1	6305.25	**0.82082**
14	7.36	0	1	5335.21	**0.84225**
16	7.36	0	1	4623.85	**0.86980**
18	7.36	0	1	4079.87	**0.89718**
20	7.36	0	1	3650.41	**0.90522**
22	7.36	0	1	3302.75	**0.91052**

24	7.36	0	1	3015.55	**0.91770**
26	7.36	0	1	2774.31	**0.92714**
28	7.36	0	1	2568.81	**0.93003**
30	7.36	0	1	2391.65	**0.93082**
32	7.36	0	1	2237.35	**0.93699**
34	7.36	0	1	2101.75	**0.93879**
36	7.36	0	1	1981.65	**0.93876**
38	7.36	0	1	1874.53	**0.94343**
40	7.36	0	1	1778.40	**0.94363**
42	7.36	0	1	1691.65	**0.94297**
44	7.36	0	1	1612.97	**0.94775**
46	7.36	0	1	1541.28	**0.94712**
48	7.36	0	1	1475.70	**0.94563**
50	7.36	0	1	1415.46	**0.94563**
10	7.36	1	1	7706.42	**0.77734**
12	7.36	1	1	6305.25	**0.83100**
14	7.36	1	1	5335.21	**0.85871**
16	7.36	1	1	4623.85	**0.89083**
18	7.36	1	1	4079.87	**0.90744**
20	7.36	1	1	3650.41	**0.91594**
22	7.36	1	1	3302.75	**0.92516**
24	7.36	1	1	3015.55	**0.93133**
26	7.36	1	1	2774.31	**0.93634**
28	7.36	1	1	2568.81	**0.93951**
30	7.36	1	1	2391.65	**0.94107**
32	7.36	1	1	2237.35	**0.94698**
34	7.36	1	1	2101.75	**0.94784**
36	7.36	1	1	1981.65	**0.94764**
38	7.36	1	1	1874.53	**0.95266**
40	7.36	1	1	1778.40	**0.95268**
42	7.36	1	1	1691.65	**0.95150**
44	7.36	1	1	1612.97	**0.95647**
46	7.36	1	1	1541.28	**0.95571**
48	7.36	1	1	1475.70	**0.95405**
50	7.36	1	1	1415.46	**0.95812**
10	7.36	2	1	7706.42	**0.79425**
12	7.36	2	1	6305.25	**0.83963**
14	7.36	2	1	5335.21	**0.87052**
16	7.36	2	1	4623.85	**0.89941**
18	7.36	2	1	4079.87	**0.91776**
20	7.36	2	1	3650.41	**0.92506**
22	7.36	2	1	3302.75	**0.93254**
24	7.36	2	1	3015.55	**0.93929**
26	7.36	2	1	2774.31	**0.94457**
28	7.36	2	1	2568.81	**0.94811**
30	7.36	2	1	2391.65	**0.94793**

32	7.36	2	1	2237.35	**0.95315**
34	7.36	2	1	2101.75	**0.95449**
36	7.36	2	1	1981.65	**0.95399**
38	7.36	2	1	1874.53	**0.95888**
40	7.36	2	1	1778.40	**0.95875**
42	7.36	2	1	1691.65	**0.95731**
44	7.36	2	1	1612.97	**0.96223**
46	7.36	2	1	1541.28	**0.96195**
48	7.36	2	1	1475.70	**0.96143**
50	7.36	2	1	1415.46	**0.96374**
10	7.36	2	2	7706.42	**0.79964**
12	7.36	2	2	6305.25	**0.84354**
14	7.36	2	2	5335.21	**0.87342**
16	7.36	2	2	4623.85	**0.90128**
18	7.36	2	2	4079.87	**0.91894**
20	7.36	2	2	3650.41	**0.92750**
22	7.36	2	2	3302.75	**0.93417**
24	7.36	2	2	3015.55	**0.94364**
26	7.36	2	2	2774.31	**0.94534**
28	7.36	2	2	2568.81	**0.94982**
30	7.36	2	2	2391.65	**0.94908**
32	7.36	2	2	2237.35	**0.95466**
34	7.36	2	2	2101.75	**0.95536**
36	7.36	2	2	1981.65	**0.95471**
38	7.36	2	2	1874.53	**0.96024**
40	7.36	2	2	1778.40	**0.95983**
42	7.36	2	2	1691.65	**0.95806**
44	7.36	2	2	1612.97	**0.96296**
46	7.36	2	2	1541.28	**0.96331**
48	7.36	2	2	1475.70	**0.96228**
50	7.36	2	2	1415.46	**0.96494**
10	7.36	1	2	7706.42	**0.77662**
12	7.36	1	2	6305.25	**0.83082**
14	7.36	1	2	5335.21	**0.85850**
16	7.36	1	2	4623.85	**0.89058**
18	7.36	1	2	4079.87	**0.90736**
20	7.36	1	2	3650.41	**0.91582**
22	7.36	1	2	3302.75	**0.92507**
24	7.36	1	2	3015.55	**0.93129**
26	7.36	1	2	2774.31	**0.93634**
28	7.36	1	2	2568.81	**0.93955**
30	7.36	1	2	2391.65	**0.94110**
32	7.36	1	2	2237.35	**0.94696**
34	7.36	1	2	2101.75	**0.94774**
36	7.36	1	2	1981.65	**0.94758**
38	7.36	1	2	1874.53	**0.95259**

40	7.36	1	2	1778.40	**0.95263**
42	7.36	1	2	1691.65	**0.95146**
44	7.36	1	2	1612.97	**0.95638**
46	7.36	1	2	1541.28	**0.95567**
48	7.36	1	2	1475.70	**0.95411**
50	7.36	1	2	1415.46	**0.95811**
10	9.2	0	1	7706.42	**0.74591**
12	9.2	0	1	6305.25	**0.78697**
14	9.2	0	1	5335.21	**0.84132**
16	9.2	0	1	4623.85	**0.86233**
18	9.2	0	1	4079.87	**0.88528**
20	9.2	0	1	3650.41	**0.90011**
22	9.2	0	1	3302.75	**0.90601**
24	9.2	0	1	3015.55	**0.91209**
26	9.2	0	1	2774.31	**0.92243**
28	9.2	0	1	2568.81	**0.92659**
30	9.2	0	1	2391.65	**0.92727**
32	9.2	0	1	2237.35	**0.93322**
34	9.2	0	1	2101.75	**0.93591**
36	9.2	0	1	1981.65	**0.93606**
38	9.2	0	1	1874.53	**0.94032**
40	9.2	0	1	1778.40	**0.94099**
42	9.2	0	1	1691.65	**0.94081**
44	9.2	0	1	1612.97	**0.94519**
46	9.2	0	1	1541.28	**0.94487**
48	9.2	0	1	1475.70	**0.94383**
50	9.2	0	1	1415.46	**0.94383**
10	9.2	1	1	7706.42	**0.75277**
12	9.2	1	1	6305.25	**0.80341**
14	9.2	1	1	5335.21	**0.85418**
16	9.2	1	1	4623.85	**0.88069**
18	9.2	1	1	4079.87	**0.89738**
20	9.2	1	1	3650.41	**0.91125**
22	9.2	1	1	3302.75	**0.91978**
24	9.2	1	1	3015.55	**0.92552**
26	9.2	1	1	2774.31	**0.93181**
28	9.2	1	1	2568.81	**0.93596**
30	9.2	1	1	2391.65	**0.93751**
32	9.2	1	1	2237.35	**0.94320**
34	9.2	1	1	2101.75	**0.94500**
36	9.2	1	1	1981.65	**0.94519**
38	9.2	1	1	1874.53	**0.94965**
40	9.2	1	1	1778.40	**0.95008**
42	9.2	1	1	1691.65	**0.94950**
44	9.2	1	1	1612.97	**0.95398**
46	9.2	1	1	1541.28	**0.95355**

48	9.2	1	1	1475.70	**0.95232**
50	9.2	1	1	1415.46	**0.95604**
10	9.2	2	1	7706.42	**0.77024**
12	9.2	2	1	6305.25	**0.81036**
14	9.2	2	1	5335.21	**0.86438**
16	9.2	2	1	4623.85	**0.88977**
18	9.2	2	1	4079.87	**0.90747**
20	9.2	2	1	3650.41	**0.92024**
22	9.2	2	1	3302.75	**0.92712**
24	9.2	2	1	3015.55	**0.93349**
26	9.2	2	1	2774.31	**0.93996**
28	9.2	2	1	2568.81	**0.94464**
30	9.2	2	1	2391.65	**0.94446**
32	9.2	2	1	2237.35	**0.95005**
34	9.2	2	1	2101.75	**0.95164**
36	9.2	2	1	1981.65	**0.95153**
38	9.2	2	1	1874.53	**0.95585**
40	9.2	2	1	1778.40	**0.95615**
42	9.2	2	1	1691.65	**0.95530**
44	9.2	2	1	1612.97	**0.95985**
46	9.2	2	1	1541.28	**0.95980**
48	9.2	2	1	1475.70	**0.95789**
50	9.2	2	1	1415.46	**0.96422**
10	9.2	2	2	7706.42	**0.77462**
12	9.2	2	2	6305.25	**0.81441**
14	9.2	2	2	5335.21	**0.86791**
16	9.2	2	2	4623.85	**0.89168**
18	9.2	2	2	4079.87	**0.90886**
20	9.2	2	2	3650.41	**0.92254**
22	9.2	2	2	3302.75	**0.92850**
24	9.2	2	2	3015.55	**0.93445**
26	9.2	2	2	2774.31	**0.94079**
28	9.2	2	2	2568.81	**0.94625**
30	9.2	2	2	2391.65	**0.94555**
32	9.2	2	2	2237.35	**0.95094**
34	9.2	2	2	2101.75	**0.95255**
36	9.2	2	2	1981.65	**0.95226**
38	9.2	2	2	1874.53	**0.95710**
40	9.2	2	2	1778.40	**0.95710**
42	9.2	2	2	1691.65	**0.95605**
44	9.2	2	2	1612.97	**0.96058**
46	9.2	2	2	1541.28	**0.96022**
48	9.2	2	2	1475.70	**0.95874**
50	9.2	2	2	1415.46	**0.96562**
10	9.2	1	2	7706.42	**0.75171**
12	9.2	1	2	6305.25	**0.80319**

14	9.2	1	2	5335.21	**0.85389**
16	9.2	1	2	4623.85	**0.88044**
18	9.2	1	2	4079.87	**0.89728**
20	9.2	1	2	3650.41	**0.91109**
22	9.2	1	2	3302.75	**0.91969**
24	9.2	1	2	3015.55	**0.92546**
26	9.2	1	2	2774.31	**0.93180**
28	9.2	1	2	2568.81	**0.93599**
30	9.2	1	2	2391.65	**0.93754**
32	9.2	1	2	2237.35	**0.94317**
34	9.2	1	2	2101.75	**0.94490**
36	9.2	1	2	1981.65	**0.94510**
38	9.2	1	2	1874.53	**0.94956**
40	9.2	1	2	1778.40	**0.95002**
42	9.2	1	2	1691.65	**0.94944**
44	9.2	1	2	1612.97	**0.95389**
46	9.2	1	2	1541.28	**0.95350**
48	9.2	1	2	1475.70	**0.95229**
50	9.2	1	2	1415.46	**0.95602**
No Cross Connection					
10	3.68	2	1	7706.42	**0.62781**
12	3.68	2	1	6305.25	**0.72482**
14	3.68	2	1	5335.21	**0.72652**
16	3.68	2	1	4623.85	**0.72965**
18	3.68	2	1	4079.87	**0.76290**
20	3.68	2	1	3650.41	**0.80006**
22	3.68	2	1	3302.75	**0.81991**
24	3.68	2	1	3015.55	**0.82635**
26	3.68	2	1	2774.31	**0.83296**
28	3.68	2	1	2568.81	**0.84418**
30	3.68	2	1	2391.65	**0.85068**
32	3.68	2	1	2237.35	**0.85841**
34	3.68	2	1	2101.75	**0.86168**
36	3.68	2	1	1981.65	**0.86547**
38	3.68	2	1	1874.53	**0.87204**
40	3.68	2	1	1778.40	**0.87397**
42	3.68	2	1	1691.65	**0.87513**
44	3.68	2	1	1612.97	**0.88061**
46	3.68	2	1	1541.28	**0.88328**
48	3.68	2	1	1475.70	**0.88328**
50	3.68	2	1	1415.46	**0.88696**

1.2. Stage 2

# of BHDs	SC length	SC height	SC width	SC comp.	PB width	PB height	PB comp.	**IndexA**
22	1	1	1	1	0	1	1	**0.95232**
22	1	1	1	2	0	1	1	**0.95045**
22	1	1	2	1	0	1	1	**0.95761**
22	1	1	2	2	0	1	1	**0.95533**
22	1	2	1	1	0	1	1	**0.95243**
22	1	2	1	2	0	1	1	**0.95053**
22	1	2	2	1	0	1	1	**0.94716**
22	1	2	2	2	0	1	1	**0.94485**
22	2	1	1	1	0	1	1	**0.97137**
22	2	1	1	2	0	1	1	**0.96330**
22	2	1	2	1	0	1	1	**0.98104**
22	2	1	2	2	0	1	1	**0.97415**
22	2	2	1	1	0	1	1	**0.97207**
22	2	2	1	2	0	1	1	**0.96364**
22	2	2	2	1	0	1	1	**0.98543**
22	2	2	2	2	0	1	1	**0.97604**
24	1	1	1	1	0	1	1	**0.95584**
24	1	1	1	2	0	1	1	**0.95451**
24	1	1	2	1	0	1	1	**0.95942**
24	1	1	2	2	0	1	1	**0.95790**
24	1	2	1	1	0	1	1	**0.95593**
24	1	2	1	2	0	1	1	**0.95457**
24	1	2	2	1	0	1	1	**0.94957**
24	1	2	2	2	0	1	1	**0.94803**
24	2	1	1	1	0	1	1	**0.97012**
24	2	1	1	2	0	1	1	**0.96583**
24	2	1	2	1	0	1	1	**0.98067**
24	2	1	2	2	0	1	1	**0.97543**
24	2	2	1	1	0	1	1	**0.97042**
24	2	2	1	2	0	1	1	**0.96610**
24	2	2	2	1	0	1	1	**0.98205**
24	2	2	2	2	0	1	1	**0.97628**
26	1	1	1	1	0	1	1	**0.96194**
26	1	1	1	2	0	1	1	**0.96043**
26	1	1	2	1	0	1	1	**0.96682**
26	1	1	2	2	0	1	1	**0.96475**
26	1	2	1	1	0	1	1	**0.96204**
26	1	2	1	2	0	1	1	**0.96051**
26	1	2	2	1	0	1	1	**0.95903**
26	1	2	2	2	0	1	1	**0.95696**
26	2	1	1	1	0	1	1	**0.97461**

26	2	1	1	2	0	1	1	**0.97093**
26	2	1	2	1	0	1	1	**0.98556**
26	2	1	2	2	0	1	1	**0.97965**
26	2	2	1	1	0	1	1	**0.97494**
26	2	2	1	2	0	1	1	**0.97122**
26	2	2	2	1	0	1	1	**0.98818**
26	2	2	2	2	0	1	1	**0.98048**

Appendix 2. Initial conditions

INIT, DL

T, 8

TR, 0.4

GM, 2.75

LIQ, T19, FILL=*0.1

LIQ, T20, FILL=*0.1

INIT, DP

T, 8.3

TR, 0

GM, 2.7

LIQ, T19, FILL=*0.1

LIQ, T20, FILL=*0.1

INIT, DS

T, 8.5

TR, 0

GM, 2.8

LIQ, T19, FILL=*0.1

LIQ, T20, FILL=*0.1

INIT, LL, 'Lightest Load Line'

T,   5.16

GM,   2

INIT, PL, 'Partial Load Line'

T,   6.02

GM,   2

Appendix 3. Moments

MOM, IMOWIND, 'IMO wind moment'

TYPE, IMOWEATHER

PARA, AK=200

MOM, SOLASPASS

TYPE, PASSENGER

PARA, SHIFT=16.4012

MOM, SOLASBOAT

CURV, CONST

MOME, 672.375

MOM, WIND

TYPE, WIND

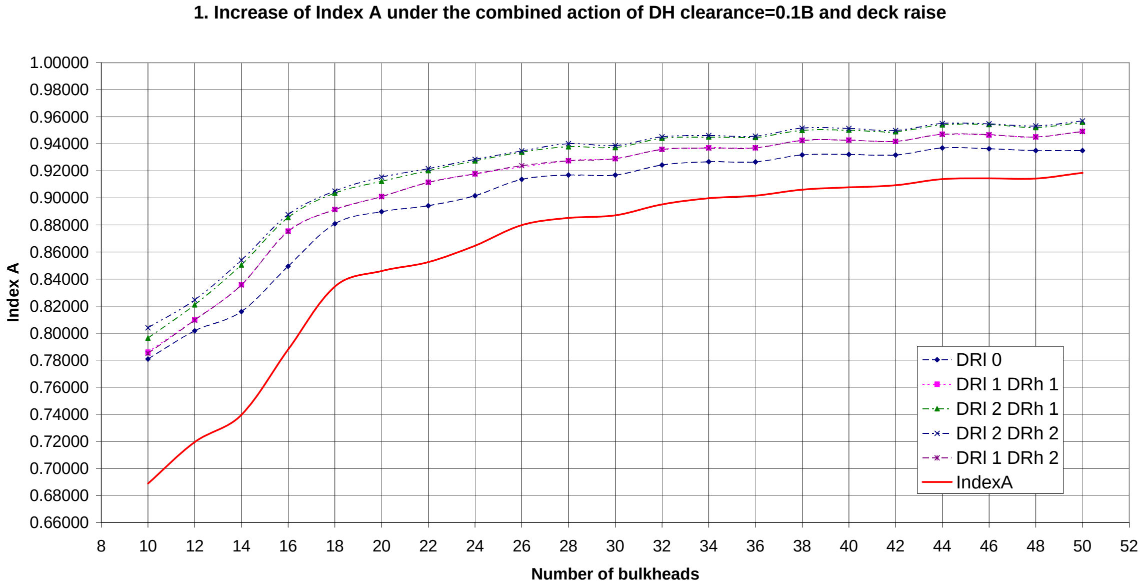
PARA, C=24.67, TP2

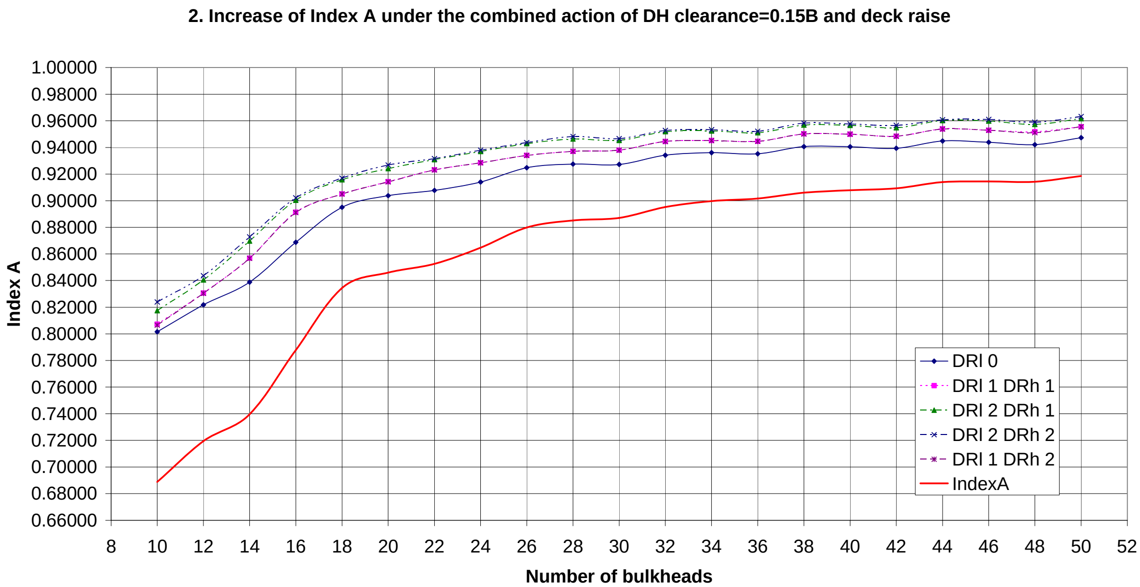
MOM, WIND20, '20m/s wind'

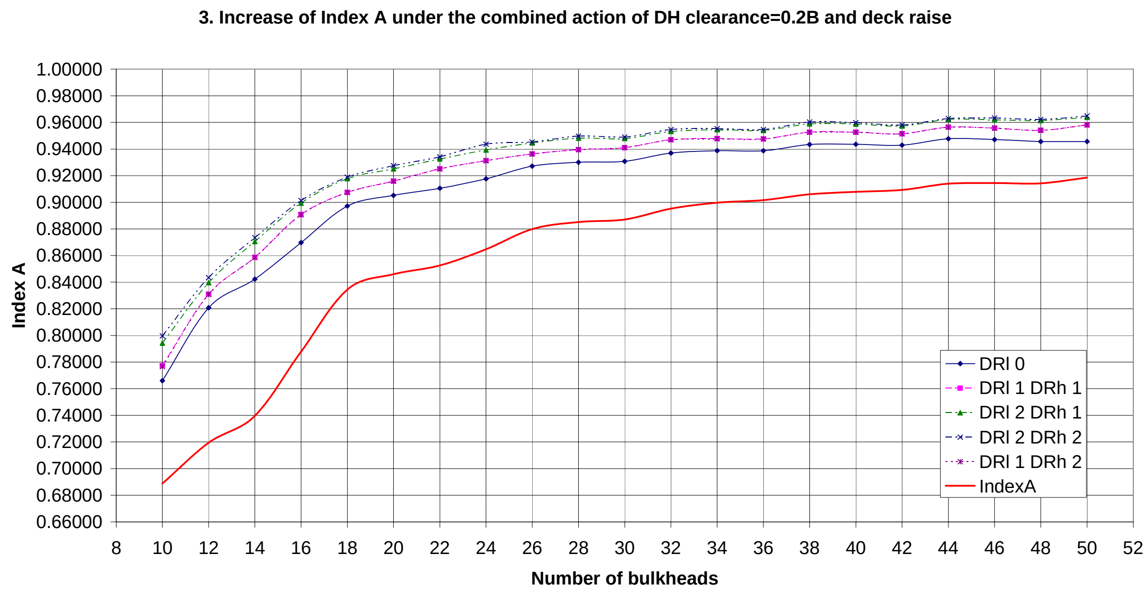
TYPE, WIND

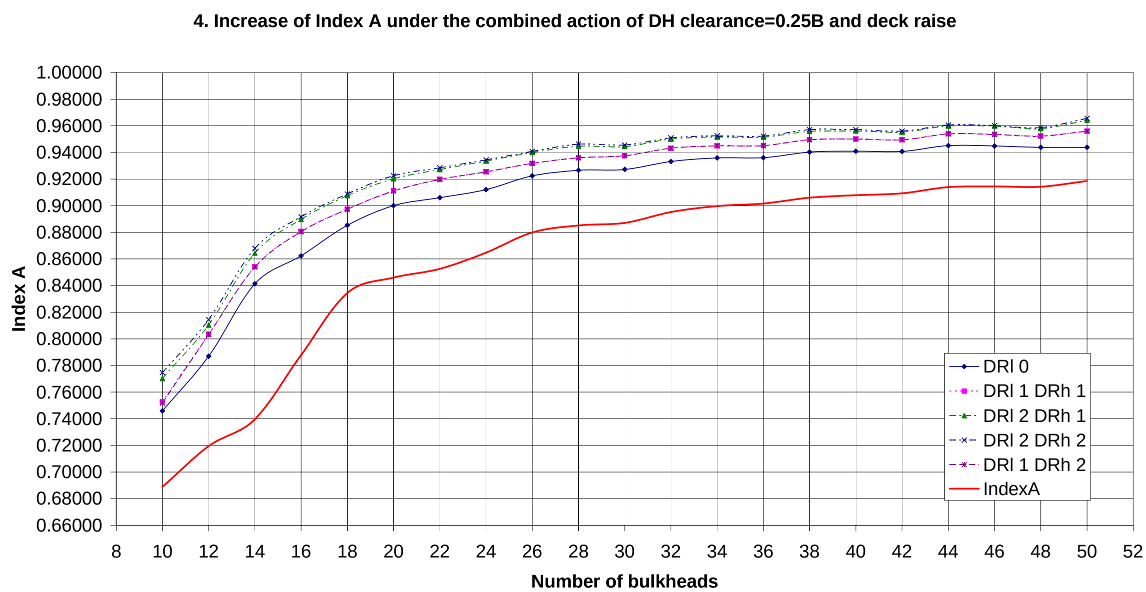
PARA, C=0.023, TP2

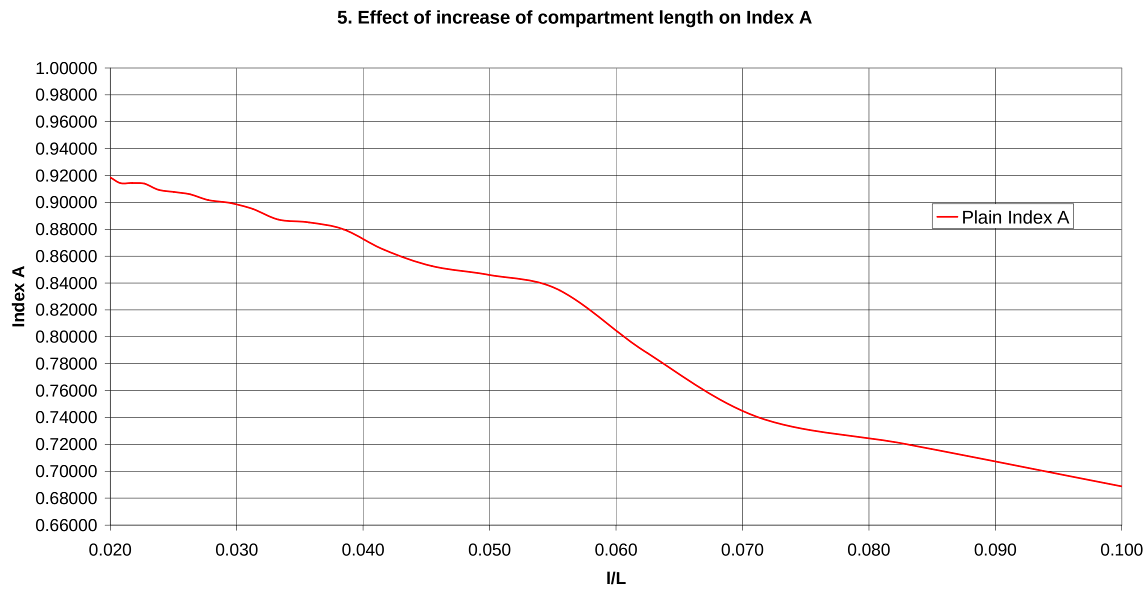
Appendix 4 Diagrams

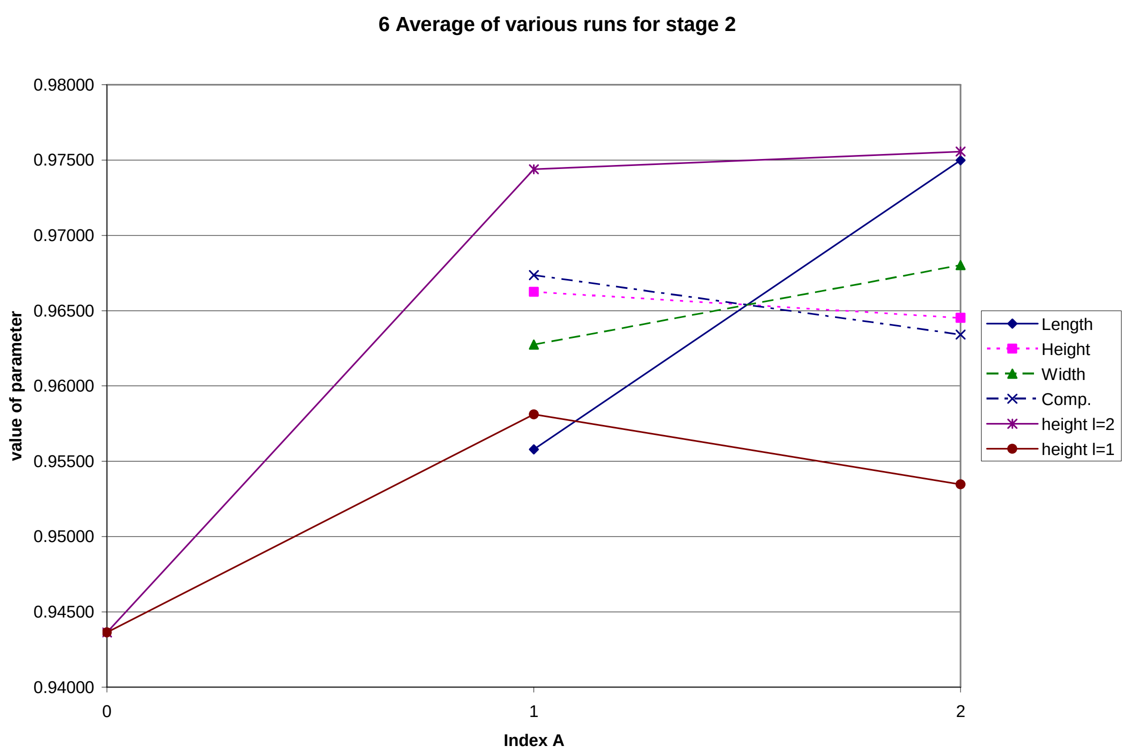





3. Increase of Index A under the combined action of DH clearance=0.2B and deck raise
Index A
Number of bulkheads
DRI 0
DRI 1 DRh 1
DRI 2 DRh 1
DRI 2 DRh 2
DRI 1 DRh 2
IndexA


4. Increase of Index A under the combined action of DH clearance=0.25B and deck raise
Index A
Number of bulkheads
DRI 0
DRI 1 DRh 1
DRI 2 DRh 1
DRI 2 DRh 2
DRI 1 DRh 2
IndexA


5. Effect of increase of compartment length on Index A
Index A
1.00000
0.98000
0.96000
0.94000
0.92000
0.90000
0.88000
0.86000
0.84000
0.82000
0.80000
0.78000
0.76000
0.74000
0.72000
0.70000
0.68000
0.66000
0.020
0.030
0.040
0.050
0.060
0.070
0.080
0.090
0.100
l/L
Plain Index A


6 Average of various runs for stage 2
value of parameter
0.98000
0.97500
0.97000
0.96500
0.96000
0.95500
0.95000
0.94500
0.94000
0
1
2
Index A
Length
Height
Width
Comp.
height l=2
height l=1