A COMPREHENSIVE APPROACH TO SURVIVABILITY ASSESSMENT IN NAVAL SHIP CONCEPT DESIGN

(DOI No: 10.3940/rina.ijme.2014.a4.307)

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SUMMARY

Alongside deploying weapons and sensors what makes a warship distinct is its survivability, being the measure that enables a warship to survive in a militarily hostile environment. The rising cost of warship procurement, coupled with declining defence budgets, has led to cost cutting, often aimed at aspects, such as survivability, which may be difficult to quantify in a manner that facilitates cost capability trade-offs. Therefore, to meet ever-reducing budgets, in real terms, innovation in both the design process and the design of individual ships is necessary, especially at the crucial early design stages. Computer technology can be utilised to exploit architecturally orientated preliminary design approaches, which have been conceived to explore innovation early in the ship design process and the impact of such issues as survivability. A number of survivability assessment tools currently exist; however, most fail to integrate all the constituent elements of survivability (i.e. susceptibility, vulnerability and recoverability), in that they are unable to balance between the component aspects of survivability. Some of these tools are qualitative and therefore less than ideal in specifying survivability requirements, others are aimed towards the more detailed design stages where implementing changes is heavily constrained or even impractical. This paper presents a survivability assessment approach combining various tools used by UCL and the UK Ministry of Defence, as well as a new approach for recoverability assessment. The proposed method attempts to better integrate and quantify survivability in early stage ship design, which is facilitated by the UCL derived, architecturally focused, design building block approach. The integrated survivability method is demonstrated for a set of naval combatant concept designs and for two replenishment ship studies to test the robustness of the proposed approach.

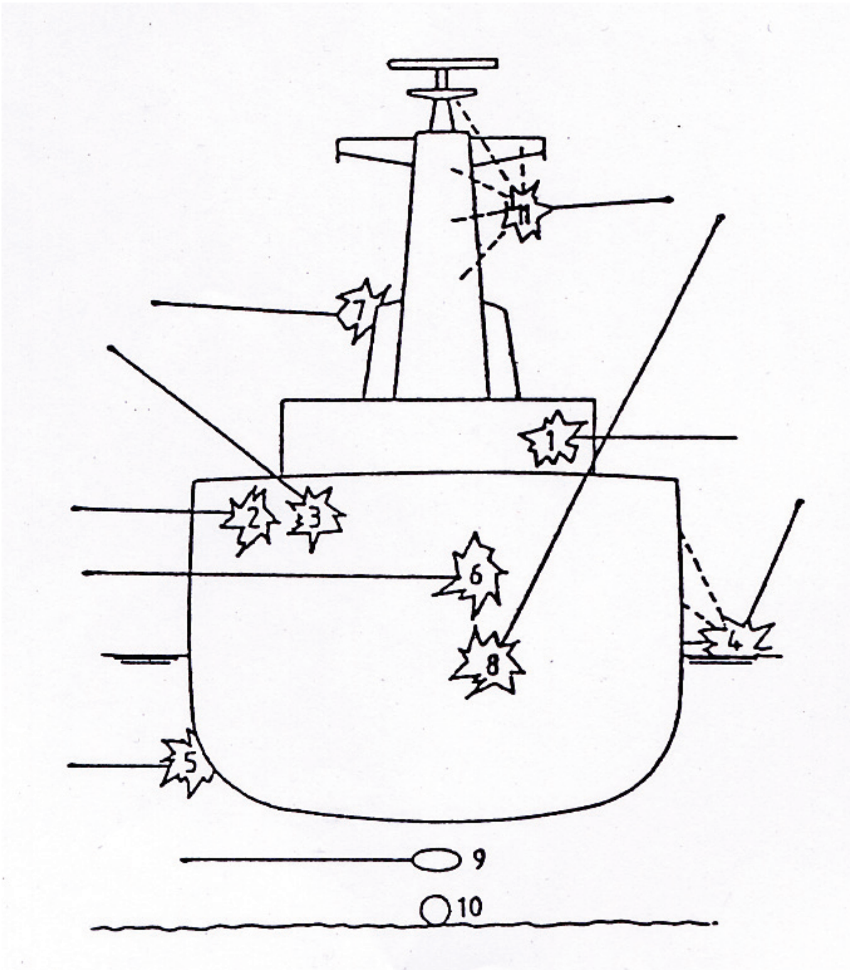
NOMENCLATURE

AAW	Anti-air Warfare
ADMS	Area-defence Missile System
AOR	Auxiliary Oiler Replenishment
ASM	Anti-ship Missile
AVCAT	Aviation Carrier Turbine fuel for aircraft
CASD	Computer Aided Ship Design
CAD	Computer Aided Design
Cdr.	Commander
CIWS	Close-in Weapon System
CSEE	Combat Systems Effectiveness Exercise (specifically used at UCL)
DBB	Design Building Block
DC	Damage Control
DCFF	Damage Control and Firefighting
Dieso	Diesel fuel, general purpose
DRC	Design Research Centre (UCL)
Dstl	Defence Science and Technology Laboratory, UK MOD
EPSRC	UK Engineering and Physical Sciences Research Council
EW	Electronic Warfare
FRP	Fire and Repair Party
GRC	Graphics Research Corporation Ltd
HQ	Headquarters
IR	Infra-red
Lt.	Lieutenant
Lt. Cdr.	Lieutenant Commander
MOD	Ministry of Defence, UK
NATO	North Atlantic Treaty Organisation
NBCD	Nuclear, Biological and Chemical Defence
P(di)	Probability of the ship being detected and identified
PDMS	Point-defence Missile System
P(h)	Probability of the ship being hit by at least one ASM
P(l)	Probability that at least one missile locks on the ship
PM	Performance Measures
RAS	Replenishment At Sea
RCS	Radar Cross Section
RN	Royal Navy
Rtd.	Retired
SAM	Surface-to-air Missile
SPECTRE	UK MOD RCS prediction software
SURFCON	Surface Ship Concept, architectural module in GRC Paramarine CASD system
SURVIVE	Surface and Underwater Ship Visual Vulnerability Evaluation tool (QinetiQ)
UCL	University College London
USS	United States Ship
WT	Watertight
WWII	World War 2

1. INTRODUCTION

Historically naval ships were designed to minimise their vulnerability to weapon attack, which could be multivarious (Figure 1). This was seen as largely the province of the naval architect and much of vulnerability practice in naval ships has drawn on WWII experience [2]. This has led to reducing the need for substantial armour (the heavy armoured battleship having been easily sunk by aircraft) and relying on WT compartmentation to meet damage stability standards in smaller combatants [3]. One of the reasons for no longer resorting to the use armour (except for relatively high and exposed magazines) was the realisation that investment in both active (PDMS/CIWS) [4] [5] and passive defence (e.g.: RCS, IR, EW measures and decoys) [6] could better counter modern weapon systems, such as supersonic air to surface missiles. The other aspect of designing for survivability in naval vessels was the ability to mitigate the effects of damage, namely recoverability, which was possible since naval vessels have relatively large and well-trained crews. The importance of recoverability has been clearly observed in various occasions, such as the Falklands Conflict (where six RN ships were sunk but twelve survived substantial damaged) [7]; the USS Stark (hit by two missiles while in the Persian Gulf in 1987) [8] and the USS Samuel B. Roberts (hit by a mine in 1988) [9]; all instances where ships were saved due to Damage Control actions.

This paper describes the research carried out during a 3.5 year project [10] at the UCL Design Research Centre (http://www.ucl.ac.uk/mecheng/research/marine) on naval ship survivability assessment in preliminary design. The basis of this research was outlined in a paper to the RINA Warship 2012: The Affordable Warship Conference [11], while the current paper presents the culmination of the research project. The project was funded by the UK Engineering and Physical Sciences Research Council and sponsored by the Maritime Integrated Survivability team (part of the Maritime Systems Engineering Group in the Naval Systems Department) of the UK Ministry of Defence's Dstl (https://www.dstl.gov.uk).



Low capacity, contact
1. cannon shell, HE and AP

High capacity, contact
2. HE shell
3. HE bomb
4. HE bomb, near miss
5. contact torpedo or mine

Medium capacity, contact
6. missile, sea skimming and SAP shell
7. missile, high level
8. medium case bomb

High capacity, non-contact
9. magnetic-fused torpedo
10. ground mine
11. proximity-fused missile

Figure 1: Available Conventional Weapons [1]

Survivability is defined by NATO as "the capability of a weapon system to continue to carry out its designated mission(s) in a combat environment" [12], where in the current case the 'weapon system' signifies a naval vessel. Survivability is generally considered to encompass susceptibility, vulnerability and recoverability [13]. Susceptibility is the measure of a ship being detected, identified, targeted and hit; vulnerability addresses the damage caused by that incident; while recoverability indicates the extent to which the vessel's capability, degraded due to damage, can be recovered and the time needed to recover it. Each of the three constituents is particularly dependent on the vessel's configuration, which, in turn, is determined during the crucial early ship design stages.

Never the less, the driving issues in preliminary ship design have traditionally been powering, stability, strength and seakeeping [14]. Therefore, survivability related issues are normally investigated in detail during the later design stages but have been heavily constrained by the major design features being determined (and largely fixed) beforehand. In addition, the lack of a survivability assessment method that is integrated and quantifiable, yet utilisable during the early design stages, means survivability is often given insufficient weight in the concept trade off process. When this is combined with rising warship procurement costs there is a temptation, in the response to the budget pressure, to see the option of cost cutting this complex and highly critical aspect as being all too attractive. This can occur despite the consequence of inadequate ship designs being selected from the concept phase with inappropriate levels of survivability.

This paper presents an approach to ship design, which produces an integrated survivability assessment [10]. It focuses on this proposed integrated survivability assessment (with an emphasis on the least mature survivability aspect of recoverability) in preliminary ship design. This emphasis is facilitated by using the architecturally orientated UCL Design Building Block approach to preliminary ship design [15]. It is considered that the use of architecturally orientated design approaches enables a balanced assessment of survivability at the earliest design stages, which are characterised by the expenditure of minimal design resources while having a large impact on the final design, in terms of vessel configuration and cost.

The feasibility of such an integrated approach to ship survivability is illustrated through the development of various ship concept designs, both naval combatants and auxiliary ships, with conventional and unconventional hullform configurations. These designs have been analysed using the DBB capability of Paramarine CASD [16] and various survivability assessment techniques, which are outlined below.

2. BACKGROUND

2.1 THE DESIGN BUILDING BLOCK APPROACH TO PRELIMINARY SHIP DESIGN

It has already been remarked that, traditionally, naval architects have focused on the areas of speed, seakeeping, stability and strength as the driving issues in preliminary ship design [14]. In contrast, 'style' related issues have been largely examined at later stages, despite the fact that warships are generally not weight or space limited, but architecturally driven [17].

Andrews' [18] proposal to integrate ship architecture with the traditional numerical techniques was followed by the demonstration of 'creative synthesis', presented in a paper entitled 'An Integrated Approach to Ship Synthesis' [19]. From this work, a new approach, namely the DBB approach [15] was developed.

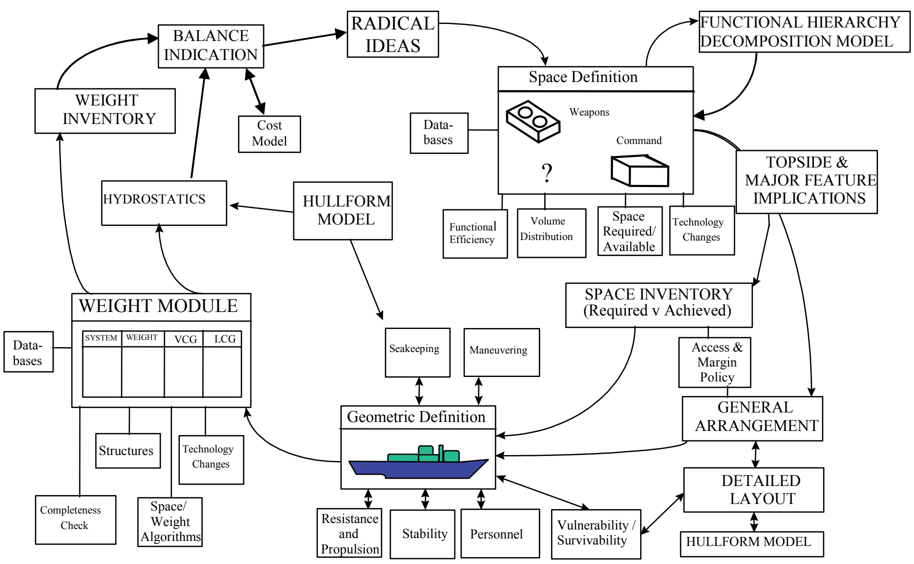


Figure 2: Building Block Design Methodology Applied to Surface Ships [15]

The basic idea behind the DBB approach is for the designer to separate the ship's functions and sub-functions into discrete physically realisable elements (Design Building Blocks) and position them appropriately in a putative ship configuration. This then puts architectural features at the centre of the ship synthesis process, in contrast to the traditional numerically based sequential design process [15]. The architectural approach allows a more thorough exploration of alternative designs to meet an emerging set of requirements, as well as encouraging the investigation of novel solutions [15] [20] to enable the true nature of early stage ship design to be met [21]. A summary of the DBB approach is given in Figure 2.

The above approach to preliminary ship design was developed and implemented following the rapid developments in computer capability through QinetiQ GRC's SURFCON implementation in their Paramarine CASD suite [16]. SURFCON's proof of concept was then described in [22]. By implementing the DBB approach through the SURFCON module in the Paramarine CASD suite, the DBB approach was linked to an already commercially established preliminary ship design software package [16]. In this way, SURFCON draws on all the naval architectural analytical tools (stability, powering seakeeping, vulnerability, manoeuvring, structural analysis, etc.) available in Paramarine [22]. Consequently, a fully integrated preliminary design process, now architecturally centred yet combined with traditional naval architectural numerical analysis techniques, enables a more realistic balance to be achieved [23]. This approach to initial ship design has been shown to be applicable to a wide range of conventional and unconventional ships in the last decade [24] and is now seen to be an accepted ship design approach [25].

2.2 SURVIVABILITY ASSESSMENT

The NATO description of survivability is summarised in Figure 3.

It is commonly accepted that the main operational difference between commercial and naval ships is that the latter will be deliberately placed in harm's way and should therefore be able to survive more extreme conditions than even the most severe imposed by the marine environment. In order to survive militarily extreme conditions, the inherent survivability, due to the nature of a ship's construction, needs to be complemented by additional survivability features [26]. These features (such as signature management and additional structural design features) constitute the main distinction between commercial and naval ship design, aside from combat systems. Such ship aspects not only increase the complexity of naval ships [27] but also are difficult to quantify as a contribution to enhancing the warship's performance [28].

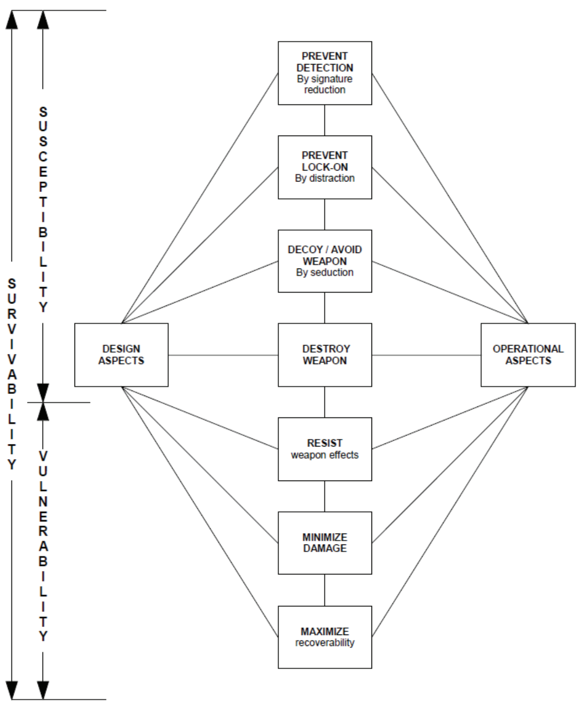


Figure 3: Survivability is a subject, which depends on the interrelation of many subjects. [12]

"Survivability assessment is the systematic description, delineation, quantification, and statistical characterisation of the survivability of a ship" [12]. In the past, the evaluation of most ship characteristics, including survivability, was perceived to be difficult [29]. In recent decades (following on from the 1982 Falklands conflict), considerable progress has been made regarding ship survivability assessment methods. Various survivability assessment methods can be used to audit a developing design, suggest improvements, improve communication between designers, builders and operators and justify the adoption of measures to enhance the survivability of a given design [30] [31]. Turner et al [32] and Randles [33] suggest that survivability assessment should not merely be an aspect of design audit, but should be carried out from the onset of the design process. By integrating such techniques in the initial design process, survivability assessment becomes another input in this iterative and investigative process [34] [35].

A number of survivability assessment tools currently exist; however, most are aimed at a single constituent of a ship's survivability (or even at a specific aspect of a survivability constituent, such as RCS [32]), being unable to balance between the various survivability measures. Other tools are qualitative, such that they are inadequate for conducting trade-offs (e.g.: as part of a safety and risk analysis [36] [37]). Further current survivability assessment tools are aimed towards the detailed design phases, where implementing substantive design changes is impractical (e.g.: personnel flow and fire simulation tools [38] [39], which generally require a detailed design description).

2.3 CONCLUSIONS ON SURVIVABILITY ASSESSMENT IN PRELIMINARY SHIP DESIGN

Given its importance and impact on the design, there is seen to be need for a simple and rapid method for fully integrating and quantifying naval ship survivability, early in design. Since survivability is layout sensitive, it is proposed that the method should take advantage of architecturally driven ship design processes so that survivability can be integrated into the initial iterative design process. By being applied to early stage design, when there is minimum detail, it also means the ship configuration is readily amenable to change. The method proposed combines a number of tools used by UCL and the UK MOD, as well as a new approach to quantify recoverability. In regard to recoverability, the proposed approach is driven by the need to overcome the difficulties of recoverability modelling (such as the lack of data, human performance and time dependence), by using weighted performance measures. The quantification of such a significant aspect of warship performance is seen to facilitate the need to better design "the most complex, diverse and highly integrated of any engineering systems" regularly produced today [40].

Effective use of survivability assessment methods is also seen as enabling designers to find a balance between the constituent components of survivability, better assess the implications of the extent of survivability reduction features on a ship's weight and cost, and to compare different, competing, ship design options [3].

3. SURVIVABILITY ASSESSMENT METHOD DEVELOPMENT

3.1 SUSCEPTIBILITY AND VULNERABILITY ASSESSMENT

A number of susceptibility and vulnerability assessment methods currently exist (such as the ones described below, used by the UK MOD). Moreover, most of those techniques can be used throughout the ship design process. Therefore, the development of new susceptibility and vulnerability assessment methods was judged unnecessary.

However, in order to demonstrate a comprehensive survivability approach, these discrete methods need to be integrated together with a new recoverability assessment method. It was therefore decided that a clear single threat scenario should be adopted for the demonstration. The scenario selected was that of a naval ship being attacked by radar homing (at 15GHz), sea-skimming Anti-Ship Missiles, given this is seen as a principal threat faced by modern warships [41] [42].

The ship being attacked would attempt to defend itself using both its soft-kill systems (chaff decoys) and hard-kill systems (ADMS, PDMS, CIWS). Three probabilities were calculated for the susceptibility part of the proposed survivability assessment method. The probability of the ship being detected and identified, $P(di)$, the probability that at least one missile locks onto the ship, $P(l)$, and the probability of the ship being hit by at least one ASM, $P(h)$.

For the calculation of these probabilities, it was decided to utilise a combination of tools:-

- The SPECTRE software, the current UK MOD RCS prediction tool [32] [43] operated by Dstl;
- The CSEE method [44], operated by UCL in support of the major ship design exercise of its MSc in Naval Architecture (http://www.ucl.ac.uk/mecheng/ourcourses/postgraduate/naval-architecture) and used to estimate defensive system (hard-kill) effectiveness;
- Various simplified and unclassified weapon data and system relationships.

With regards to vulnerability assessment, the software utilised was QinetiQ's SURVIVE Lite [45] [32], the principal vulnerability assessment code used by the UK MOD for the ship concept phase. Use of full SURVIVE would have been inappropriate at the concept level of design definition, even with the DBB configurations available in this research. SURVIVE Lite is able to simulate a large variety of threat types, including ASMs.

It was decided that a limited amount of major ship systems/capabilities should be initially modelled to be consistent with initial ship design. It would also ease the proof of the concept of an integrated survivability assessment approach and was felt to address the most likely main ship capabilities relevant to survivability. Thus, as shown below for the naval combatant design studies, the Move system as a whole and the main Fight component elements were modelled :-

- Move system;
- Naval gun system;
- Ship ASM system;
- Aft SAM system;
- Fwd SAM system;
- Helicopter system.

And for the naval auxiliary ship design studies :-

- Move system;
- Ability to RAS AVCAT;
- Ability to RAS dieso;
- Ability to RAS dry stores;
- Ability to RAS ordnance;
- Aviation support;
- CIWS.

Since the modelled ship systems just listed do not have equal significance to a given ship design's effectiveness and are highly dependent on the operational scenario undertaken by the ship, weighting schemes were applied to these systems before obtaining the final vulnerability data. The weighting schemes were obtained by interviewing naval officers at UCL and Dstl [10].

In addition, vulnerability analysis was conducted on the basis of a hit sustained in each watertight section of each ship design, in isolation and in turn (Figure 4).

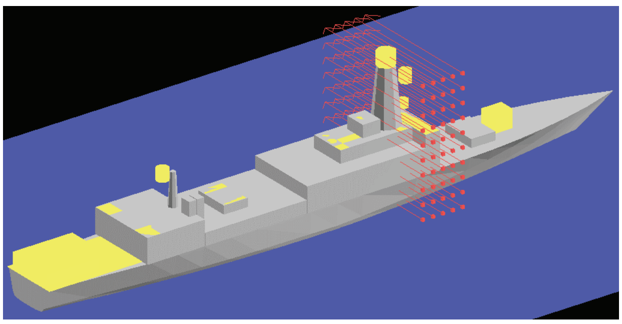


Figure 4: Frigate Variant 1 Hit Grid Input to SURVIVE Lite Simulation (for Starboard Side Attack)

The vulnerability data for each of the listed systems was then averaged over the length of the modelled ship, in order to obtain average vulnerability values [10].

In addition to the above systems and their components, other equipment and compartments, such as Air Treatment Units, firepumps, Nuclear Biological and Chemical Defence stores, Fire Repair Party section bases, workshops, naval stores, spare gear stores and NBCD HQ 1 and HQ 2 were also modelled in SURVIVE Lite. These items were modelled in order to obtain vulnerability data of features of the given ship study that were seen to be important to recoverability. They were obtained from the hits modelled in the vulnerability analysis, which could then be used in the recoverability part of the proposed approach.

3.2 RECOVERABILITY ASSESSMENT

Modelling recoverability was seen as the most demanding area of survivability assessment for a number of reasons. These included the limited ability to model the effect of secondary damage and crew actions on recoverability metrics, the inadequate data available and the difficulty of incorporating metrics reflecting crew readiness and skill levels, seen to be essential in recoverability assessment. A number of recoverability assessment techniques currently exist, however, many, such as safety and risk analysis methods [36] [37], are qualitative. Thus, they are rather subjective, given they usually rely on expert judgment and, furthermore, do not take specific ship architectural features into account. This means they are considered to be of limited use in assisting the designer in making early choices on ship configuration.

However, safety and risk techniques could possibly be useful when deciding on what DC equipment to have on board and what DC procedures to follow. Other methods focus on a particular aspect of recoverability, such as fire spread or DC crew evolutions/personnel movement [38] [39]. Such methods rely on simulations and are therefore seen to be more appropriate to a relatively detailed ship definition. A tool aimed specifically at preliminary ship design did not seem to exist; neither did one specifically investigating how ship configuration/layout/architecture would affect overall naval ship recoverability. This is because recoverability is seen to be more heavily reliant on operational/human factors, rather than classical ship design factors. It was, therefore, decided that a new recoverability assessment method should be developed, one able to investigate such issues at an early stage design.

By applying the proposed recoverability method to early stage design, where there is limited and changeable detail, options for ship layout could be relatively easily investigated. It was decided that, due to their multiple run nature (to produce, for example, personnel related statistics), simulations were probably not appropriate for the level of ship definition in the ship design studies produced in this research. However, assessment of recoverability requires temporal metrics, such as the time taken to repair systems, which could be obtained from simulation. An alternative analytical method was thus required to generate this data. It was determined that the new recoverability assessment approach would work on the basis of developing a number of Performance Measures (PMs), together with an appropriate weighting scheme which might overcome the difficulties in recoverability modelling. The PM method was inspired by work such as [36] and [46]. PMs relevant to recoverability were derived from existing work, such as [36], [39] and [46] as well as through interviewing conducted with various naval officers [10]. Values for the PMs were obtained from explicit damage scenarios modelled using the Paramarine and SURVIVE Lite tools.

3.2 (a) Category 1 Performance Measures

The PMs developed were split into three categories. Weighting schemes of all PMs were derived with the assistance of various naval officers at Dstl and on postgraduate courses at UCL. Confidence in this approach was obtained by conducting sensitivity studies on the applied weighting scheme (and other features: see [10] for more detail). The approach adopted was such that the larger the value of a specific PM then the worst its recoverability performance, also that some PMs would have specific units while others would be dimensionless (see Tables 1, 2 and 3).

The first category, which is detailed in Table 1, consists of PMs related to the immediate effects on DCFF. The combatant weighting scheme presented in this paper was provided by Portuguese Navy 1st Lt. P. Fonseca, formerly a damage control officer on a frigate. The AOR weighting scheme was provided by Lt. Cdr. T. Day, RN (Rtd.), who had been an INVINCIBLE Class aircraft carrier NBCD officer and was the Dstl Maritime Integrated Survivability Team Leader at the time of this research.

3.2 (b) Category 2 Performance Measures

The second category of PMs, together with the associated weighting schemes, given in Table 2, relates to the items necessary for the recovery of the major systems once secondary effects (e.g.: fire) have been dealt with. 'Major system recovery' refers to the systems modelled and listed in Section 3.1 for the combatants and naval auxiliary design studies, respectively. From Dstl data on man-hours to recover relevant equipment categories, provided by QinetiQ during development of their full SURVIVE software, estimated man-hours were selected for the much more limited (i.e. concept level) ship arrangements available for the comparisons undertaken [10].

Table 1: Immediate DCFF Performance Measures (Category 1)

	PM	**Software**	**Weighting**	
			Combatant	**AOR**
1.1	Average distance between FRPP and damaged WT section (m)	Paramarine	7	4
1.2	Average number of WTD operated per FRP	Paramarine	4	4
1.3	Number of internal decks in damaged WT section	Paramarine	6	5
1.4	Average total width of alternative passageways (inverse) (m)	Paramarine	7	2
1.5	ATU and Ventilation (of damaged zone) (man-hours)	SURVIVE Lite	8	9
1.6	Firepump (of damaged zone) (man-hours)	SURVIVE Lite	2	1
1.7	Overall firepump system (man-hours/no of equipment)	SURVIVE Lite	8	10
1.8	NBCD stores - aft FRP section base	SURVIVE Lite	1	1
1.9	NBCD stores - fwd FRP section base	SURVIVE Lite	1	1
1.10	Remaining NBCD stores	SURVIVE Lite	2	1
1.11	Power (of damaged zone) (man-hours)	SURVIVE Lite	2	1
1.12	Overall power system (man-hours/no of equipment)	SURVIVE Lite	8	10
1.13	SCC (HQ1) (man-hours)	SURVIVE Lite	6	6
1.14	Bridge (HQ2) (man-hours)	SURVIVE Lite	2	4
1.15	Ops. Room (man-hours)	SURVIVE Lite	6	10
1.16	Aft FRPP	SURVIVE Lite	10	5
1.17	Fwd FRPP	SURVIVE Lite	10	5

Table 2: Major System Recovery Performance Measures (Category 2)

	PM	Software	Weighting	
			Combatant	AOR
2.1	Aft workshops (man-hours)	SURVIVE Lite	3	5
2.2	Fwd workshops (man-hours)	SURVIVE Lite	3	5
2.3	Naval stores	SURVIVE Lite	1	2
2.4	Aft spare gear stores	SURVIVE Lite	7	5
2.5	Fwd spare gear stores	SURVIVE Lite	7	5
2.6	SCC (updated value) (man-hours)	SURVIVE Lite	6	9
2.7	Ops. Room (updated value) (man-hours)	SURVIVE Lite	7	8

Table 3: Individual Major System Recovery Performance Measures (Category 3)

	PM	Software	Weighting	
			Combatant	AOR
3.1	Minimum man-hours for system to be functioning	SURVIVE Lite	10	10
3.2	Number of man-hours for system to be 100%	SURVIVE Lite	3	5
3.3	Access measure from naval stores	SURVIVE Lite and Paramarine	1	2
3.4	Access measure from aft spare gear stores	SURVIVE Lite and Paramarine	3	5
3.5	Access measure from aft workshops	SURVIVE Lite and Paramarine	2	5
3.6	Access measure from fwd spare gear stores	SURVIVE Lite and Paramarine	3	5
3.7	Access measure from fwd workshop	SURVIVE Lite and Paramarine	2	5
3.8	Equipment in damaged section measure	SURVIVE Lite and Paramarine	8	10

3.2 (c) Category 3 Performance Measures

The third and final PM group is listed in Table 3, together with the associated weighting scheme. This category includes PMs relevant to the recovery of the specific major systems that were modelled, which have been listed in Section 3.1. The Category 3 PMs were applied to all of those major systems, in a manner that is described in Section 3.2 (e).

3.2 (d) Performance Measures Quantification

PMs 1.1-1.4 in Table 1 are related to the ease of access to the damaged part of the ship from the FRP section bases. Values for those PMs were taken directly from the layouts given by the Paramarine CAD models of the ship design studies.

Values for the remaining PMs in Table 1, all of which have the indication 'SURVIVE Lite' in the software column, were obtained by means of the following procedure:

- First, the output from the SURVIVE Lite models indicated if the specified equipment/compartment had been affected by a specific hit;
- All unaffected items were given a value of zero;
- The affected items, i.e. all items with vulnerability greater than 0% (with the exception of PMs 1.8-1.10 and 1.16-1.17) were given a PM value based on the assumed number of man-hours to repair that specific equipment. Man-hour data for the repair of various equipment categories were provided by the sponsor (Dstl) and were the same values that had been employed by SURVIVE in its recently developed recoverability module [10].
- PMs 1.8-1.10 (related to NBCD stores) and 1.16-1.17 (related to FRP personnel) were assumed to be unrecoverable and were, therefore, given a value of zero, if unaffected by a hit, and 1, if affected.

The above approach was also applied to the PMs in Table 2 and PMs 3.1 and 3.2 in Table 3 (investigating the post-hit availability of various equipment and compartments), all of which have the indication 'SURVIVE Lite' in the software column.

PMs 3.3-3.8 reflect the difficulty in accessing equipment, which has been damaged after a specific attack and, therefore, the effort required to repair it. These access measures (PMs 3.3-3.8) were quantified by multiplying the criticality of affected equipment items by the number of man-hours needed to repair that equipment item, once it had been affected by the specific hit, which had been revealed by SURVIVE Lite. Criticality, in this context, is defined as:

$$\text{Criticality} = 1 \div (\text{number of parallel equipment items (for a specific major system)})$$

For example, if there are four engines in a ship, all providing the same capability, each has a criticality of ¼. However, PMs 3.3-3.7 were only applied to damaged equipment requiring personnel to cross the damaged WT section, in order to get access from the corresponding store/workshop. In addition PM 3.8 was obtained by multiplying the criticality by the number of man-hours needed to repair each equipment item, which was both affected by the given hit and was located in the damaged WT section in question.

3.2 (e) Performance Measures Matrix

As mentioned in Section 3.1, SURVIVE Lite was run separately to simulate an ASM hit at each WT section of each ship designed (Figure 4). Therefore, values for all PMs were obtained for a given hit at each WT section. PM matrices, such as the one shown in Table 4[1] (for a combatant), were then completed to analyse the recoverability of each ship design study. This procedure is explained in more detail in the following paragraphs. (Note that Table 4 includes an example row illustrating the PM matrix quantification procedure for the baseline combatant design, Frigate Variant 1.)

Firstly, from columns 1 and 2 of Table 4, it can be observed that the Category 3 PMs were applied to all of the major ship and combat systems modelled. This is because those PMs are related to the recovery of the specific major systems modelled (see Section 3.1). The weightings in column 3 are those for each individual PM detailed in Tables 1, 2 and 3.

Columns 4, 6, 8… of Table 4 represent all of the WT sections of each analysed ship design. In the cells of these columns, the values of the corresponding PMs (from column 2) were entered. This gave values for all PMs for a separate hit at each WT section of each ship. The values of each PM for each WT section's attack scenario were then multiplied by the probability that that WT section was hit (assuming a reasonable lengthwise probability hit distribution, identical to the one used in the vulnerability assessment, Section 3.1), and the results entered in the cells of columns 5, 7, 9… in Table 4.

The next step (column 11 of Table 4) was to compute the sum of columns 5, 7, 9… along the entire length of the ship being analysed. Thus, summing the products of the value of each PM, for each WT section's attack scenario and the probability that that WT section has been hit, gave the total value of each of the 32 PMs developed. In column 12, these total PM values were normalised with respect to the corresponding values of a baseline ship design (see Section 4), and in column 13, the normalised PM values were weighted, using the weightings in column 3 (taken from Tables 1, 2 and 3).

The sum of the normalised and weighted PM values was then computed for each PM Category (column 14 of Table 4). For Category 3 PMs, a separate sum was produced for each of the major systems modelled. These group sums were then, once again, normalised with respect to the corresponding values of the same baseline ship (column 15 of Table 4). Finally, these normalised group sums were weighted (column 17 of Table 4) with the group weightings (column 16 of Table 4). The group weightings are shown in Table 5 for the case of a combatant. As before, this combatant weighting scheme was derived with the assistance of 1st Lt. P. Fonseca, Portuguese Navy.

Table 5: Recoverability Weighting Scheme for a Combatant

Group Description		***PM cat.***	***Group Weighting***
FLOAT		Cat. 1 PMs	**10**
Recovery support		Cat. 2 PMs	**2**
MOVE	**Move system**	Cat. 3 PMs	**9**
FIGHT	**Naval gun system**		**2**
	ASM system		**2**
	Aft SAM system		**1**
	Fwd SAM system		**1**
	Helicopter system		**2**

In order to maintain consistency, the weighting scheme adopted for the above Move and Fight groups was made identical to that used in the vulnerability assessment element of the proposed approach (Section 3.1).

Table 7: Recoverability Weighting Scheme for a Replenishment Ship

Group Description		***PM cat.***	***Group Weighting***
FLOAT		Cat. 1 PMs	**10**
Recovery support		Cat. 2 PMs	**3**
MOVE	**Move system**	Cat. 3 PMs	**10**
FIGHT	**Ability to RAS AVCAT**		**10**
	Ability to RAS dieso		**10**
	Ability to RAS dry stores		**6**
	Ability to RAS ordnance		**8**
	Aviation support		**2**
	CIWS		**3**

A similar procedure, with minor alterations, was followed for the Auxiliary ship designs (see Tables 6 and 7). Note that Table 6[2] includes an example row illustrating the PM matrix quantification procedure for AOR Variant 1. The weighting scheme in Table 7 was provided by Lt. Cdr. T. Day, RN (Rtd.). In Table 6 it can be observed that all normalisations in the recoverability analysis of the AOR ship designs have been conducted with respect to the worst performing design, rather than a baseline design. This was done since both AOR design studies included PM Categories with a value of zero (indicating unaffected items after a given hit). Thus, dividing (during the normalisation process) by zero is avoided, since this would lead to impossible values. This is further detailed in [10].

[1] See Appendix for Table 4

[2] See Appendix for Table 6

4. SHIP DESIGN STUDIES

In total, seven designs were developed through the duration of the research project. Five were combatant type ships and the remaining two were AOR type ships.

Survivability was seen to be largely dependent on ship architecture and additionally the recoverability assessment method developed was specifically aimed at looking at how ship layout affects recovery from attack damage. It was therefore decided that the ship designs, on which the survivability method should be applied, would be designed by means of an architecturally orientated preliminary ship design approach. The Design Building Block approach to preliminary ship design, through its SURFCON implementation in the Paramarine CASD software (Section 2.1) was adopted, given its extensive use by the UCL DRC.

All ship studies produced in this investigation were designed and sized according to the procedures, data and parametric relationships available from the ship design exercise in the MSc in Naval Architecture at UCL [47] [48]. In addition all studies were designed with the intent of maximising survivability based on guidance gleaned from relevant literature, much of which has been referenced in this paper, with the full listing given in [10]. Thus, measures adopted included concentration and separation of duplicated ship systems, the design of all superstructure sides incorporating a 7^{o} tumblehome and the hull above the waterline having a similar (outward) flare.

4.1 FRIGATE DESIGN STUDIES

Three general purpose ocean going frigates were designed to the full concept design level. Thus they were designed to be balanced, in weight and space, hydrostatics, resistance and propulsion, commensurate with the end of the concept phase [22]. They were fitted with identical weapon fits and met the same performance requirements. The baseline frigate (Frigate Variant 1) is a typical modern frigate with a one passing deck hull and a continuous superstructure out to the ship's side. Frigate Variant 2 is characterised by the adoption of a deeper hull with two passing decks over the machinery spaces and a minimal superstructure, and was influenced by the work done by Begg et al [49]. For the third and final variant, Frigate Variant 3, a trimaran configuration was selected, departing even more substantially from the style of current conventional frigates.

The principal particulars of the three frigate variants are presented in Table 8, while Paramarine representations of the three ship designs are illustrated in Figure 5. Note that in the case of the baseline frigate, Figure 5 depicts a functional breakdown of the ship design, typical of the DBB approach to preliminary ship design [22]. The illustration shows all equipment and compartments (i.e. design building blocks) belonging to the Float functional group in blue, Move functional group in yellow, Fight functional group in red and finally Infrastructure functional group in green. In addition, from Figure 5 it is possible to examine in isolation the arrangement of the DBBs related to each of the recoverability PMs. Figure 6 shows the distribution of compartments and equipment related to Category 1 and Category 2 PM analysis (from Tables 1 and 2). Category 3 PM analysis involves all of the components of each major ship system so these cannot be easily illustrated at this level of representation.

Functional breakdown illustrations and figures depicting the arrangement of the DBBs related to each of the recoverability related PMs are included in [10] for all ship design studies.

Table 8: Summary of the Principal Particulars of the Frigate Variant Design Studies Investigated

Variant 1	
Dimensions	132.2m × 16.1m × 9.7m (deep draught 4.0m)
Displacement	3,890te deep, 3,270te light
Maximum Speed	30.5kts
Range	7,100nm at 15kts, 6,000nm at 18kts
Power Plant	1 × 31MW GT (boost), 2 × 2.94MW diesels (cruise), 2 × 2.69MW diesels (auxiliary) driving two FPPs on 20MW HTS motors
Accommodation	11 officers, 137 ratings, 25 embarked forces
Variant 2	
Dimensions	125.2m × 16.1m × 12.1m (deep draught 4.4m)
Displacement	4,060te deep, 3,450te light
Maximum Speed	30.4kts
Range	7,000nm at 15kts, 5,900nm at 18kts
Power Plant	1 × 31MW GT (boost), 2 × 5.22MW diesels (cruise), 2 × 2.69MW diesels (auxiliary) driving two FPPs on 21MW HTS motors
Accommodation	11 officers, 141 ratings, 25 embarked forces
Variant 3	
Dimensions	150.3m × 29.2m × 12.3m (deep draught 5.2m)
Displacement	4,330te deep, 3,820te light
Maximum Speed	31.3kts
Range	7,000nm at 15kts, 5,900nm at 18kts
Power Plant	1 × 31MW GT (boost), 2 × 2.94MW diesels (cruise), 2 × 2.69MW diesels (auxiliary) driving one FPP on a 37MW HTS motor and one pump-jet on a 3.5MW HTS motor
Accommodation	12 officers, 152 ratings, 25 embarked forces

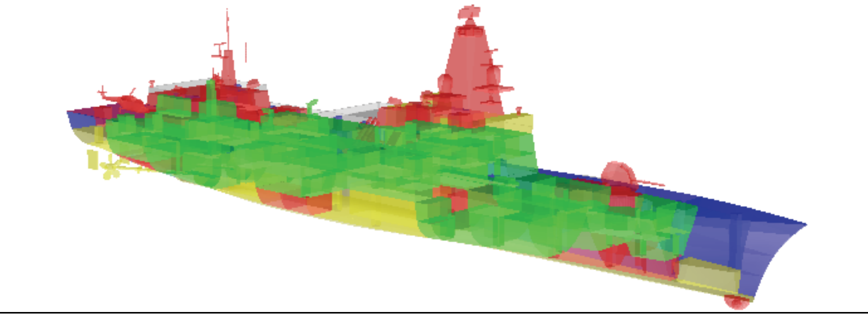
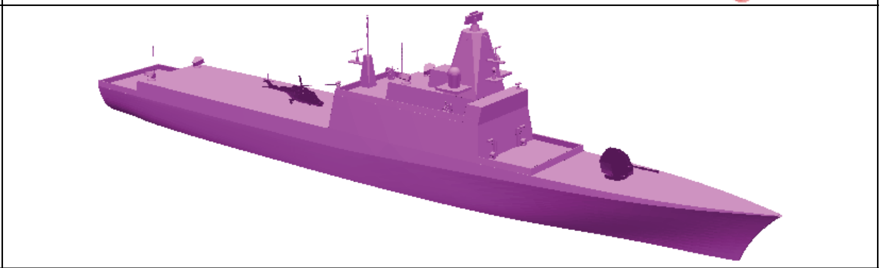
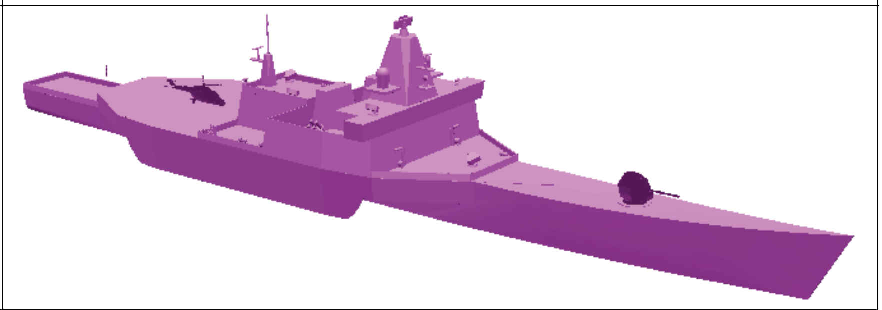
<table>
<tr><td>Frigate Variant 1
(DBB functional breakdown)</td><td></td></tr>
<tr><td>Frigate Variant 2</td><td></td></tr>
<tr><td>Frigate Variant 3</td><td></td></tr>
</table>

Figure 5: Paramarine Overall Representation of the Three Frigate Variants Ship Design Studies

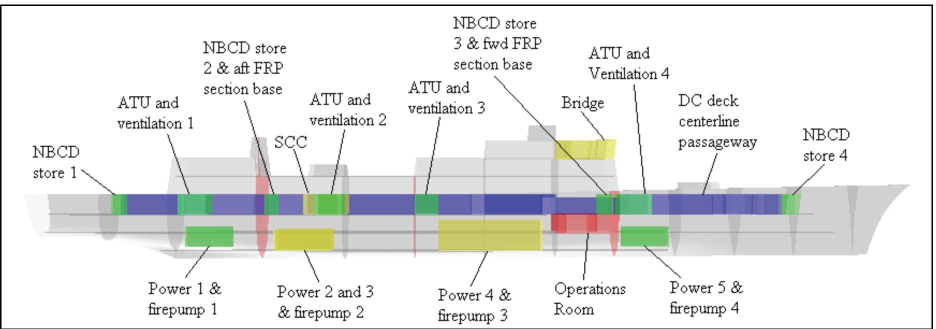
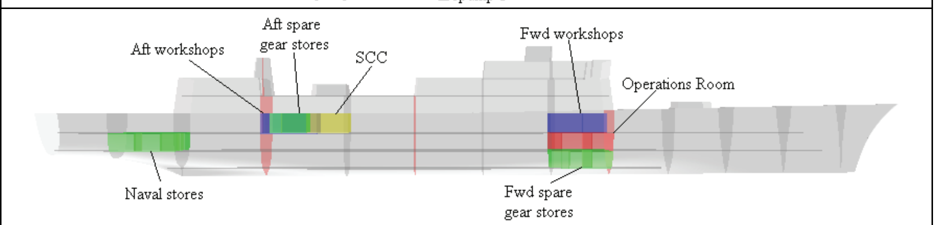
<table>
<tr><td>Category 1 PM Elements</td><td>
</td></tr>
<tr><td>Category 2 PM Elements</td><td>
</td></tr>
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Figure 6: Frigate Variant 1 with Category 1 and 2 Performance Measure Elements Highlighted

4.2 CORVETTE AND DESTROYER DESIGN STUDIES

It was decided that it would be beneficial to apply the survivability assessment method, discussed in Section 3, to combatants of different sizes to investigate the way in which each aspect of survivability is affected by ship size. This included varying the number of zones and the extent of the combat system and ship performance capabilities (appropriate to the ship type). Thus, a further two combatant design studies were produced; one smaller combatant (corvette) and one larger combatant (destroyer). These two additional combatant design studies were compared to the baseline frigate by applying the proposed survivability assessment just outlined.

Principal particulars and Paramarine overall representation of the two additional combatant designs are illustrated in Table 9 and Figure 7, respectively.

4.3 REPLENISHMENT SHIP DESIGN STUDIES

The proposed survivability assessment method was also applied to AOR type ships in order to demonstrate the applicability of the method on non-combatant, but naval, ship types. Two AOR design studies were carried out to investigate the impact of varying the internal and external configuration on survivability. AOR Variant 1 includes a split forward and aft superstructure arrangement with the RAS infrastructure located between the two blocks (analogous to the Royal Fleet Auxiliary FORT VICTORIA Class replenishment oiler); AOR Variant 2 includes a single aft superstructure block, with the RAS infrastructure slightly forward of amidships (comparable to the Royal Fleet Auxiliary WAVE Class tankers).

Principal particulars and Paramarine overall representation of the two balanced AOR designs are summarised in Table 10 and Figure 8 respectively.

Table 9: Summary of the Principal Particulars of the Corvette and Destroyer Design Studies Investigated

Corvette	
Dimensions	90.7m × 13.7m × 8.5m (deep draught 3.9m)
Displacement	1,830te deep, 1,640te light
Maximum Speed	29.7kts
Range	3,000nm at 15kts, 2,500nm at 18kts
Power Plant	1 × 24.05MW GT (boost), 2 × 1.2MW diesels (cruise), 2 × 1.2MW diesels (auxiliary) driving one FPP on a 25.5MW HTS motor and one pump-jet on a 1MW HTS motor
Accommodation	10 officers, 64 ratings
Destroyer	
Dimensions	154.0m × 18.9m × 12.4m (deep draught 4.7m)
Displacement	6,250te deep, 5,120te light
Maximum Speed	29.7kts
Range	8,000nm at 15kts, 7,200nm at 18kts
Power Plant	1 × 31MW GT (boost), 2 × 4.08MW diesels (cruise), 2 × 5.44MW diesels (auxiliary) driving two FPPs on 20MW HTS motors
Accommodation	22 officers, 151 ratings, 50 embarked forces

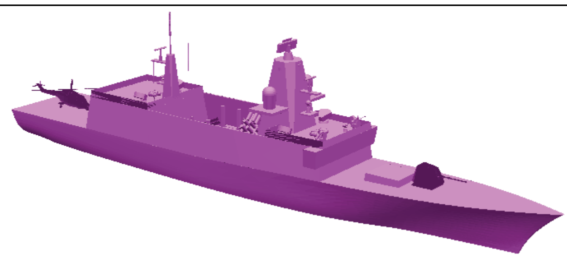
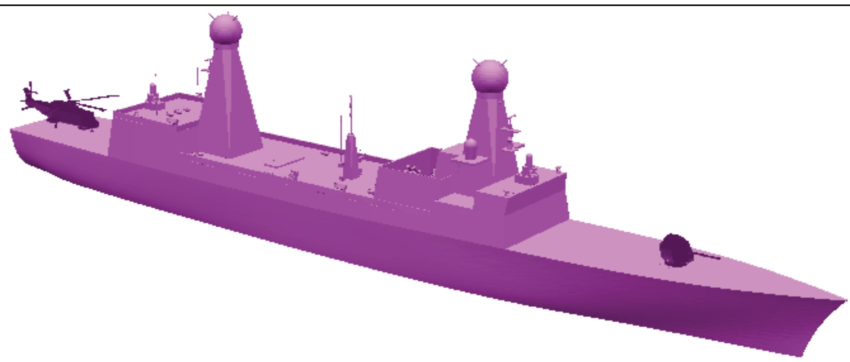
Corvette	
Destroyer	

Figure 7: Paramarine Overall Representation of the Corvette and Destroyer Design Studies

Table 10: Summary of the Principal Particulars of the AOR Variant Design Studies Investigated

Variant 1	
Dimensions	205.4m × 28.2m × 20.4m (deep draught 12.0m)
Displacement	38,450te deep, 23,620te light
Maximum Speed	18.3kts
Range	15,300nm at 15kts, 11,400nm at 18kts
Power Plant	4 × 5.76MW diesels (cruise and auxiliary), 1 × 0.685MW diesel (emergency) driving two 10MW pods and one pump-jet on a 1MW HTS motor.
Accommodation	30 officers, 183 ratings
Variant 2	
Dimensions	205.4m × 28.2m × 20.4m (deep draught 11.9m)
Displacement	37,850te deep, 23,360te light
Maximum Speed	18.3kts
Range	15,600nm at 15kts, 11,600nm at 18kts
Power Plant	4 × 5.76MW diesels (cruise and auxiliary), 1 × 0.685MW diesel (emergency) driving two 10MW pods.
Accommodation	30 officers, 183 ratings

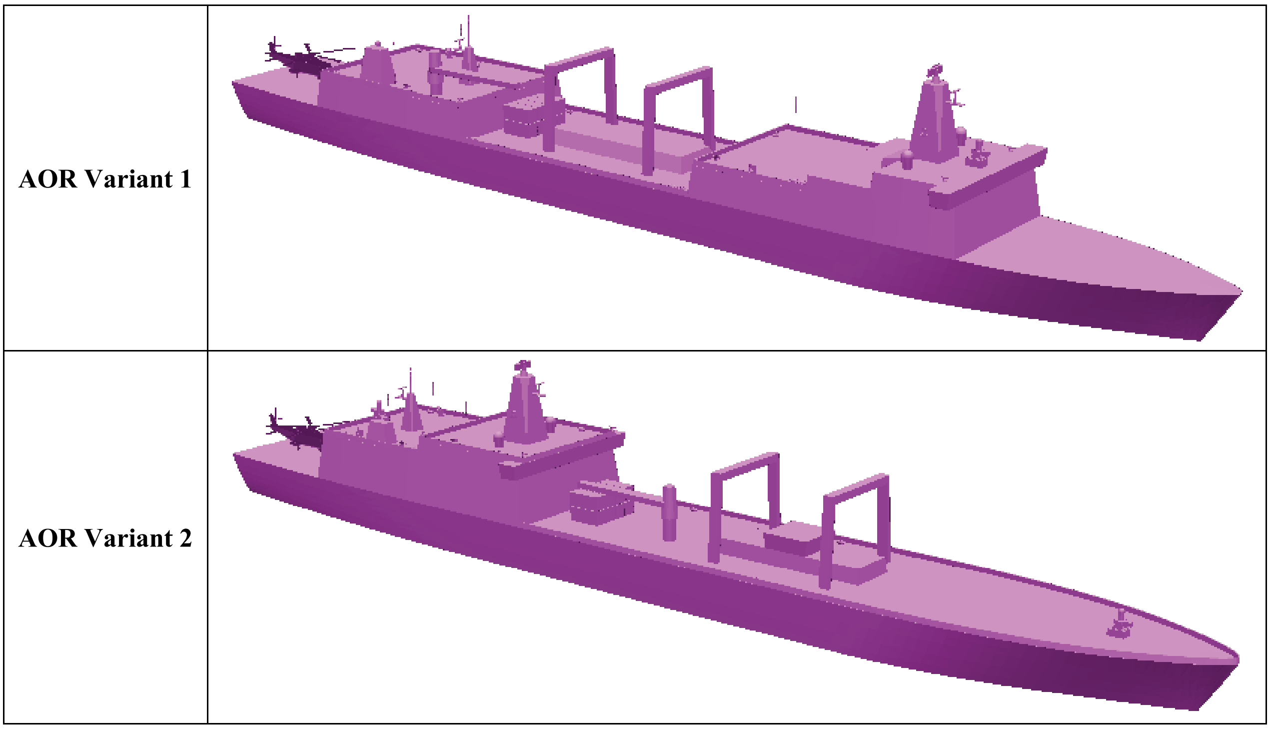


Figure 8: Paramarine Overall Representation of the AOR Design Studies

5. RESULTS OF APPLYING PROPOSED SURVIVABILITY ASSESSMENT APPROACH

The research project produced a substantial quantity of results for the three survivability constituents and for all seven ship designs produced [10]. This section summarises the overall survivability results of the ship design studies presented in Section 4 against the threat outlined in Section 3.1.

Figure 9 presents the total survivability results for the three frigate variants in the form of a star plot. The data presented are normalised with respect to the baseline frigate, hence the performance of Frigate Variant 1 is unity for each survivability constituent. In order to maintain consistency with susceptibility and vulnerability (for which the higher the value, the worse the performance), "difficulty of recoverability" was computed, rather than "recoverability" itself. Therefore, each star plot (a triangle in this case) represents a specific ship design and the smaller the area of the triangle, the more survivable that design is against the particular ASM threat.

Similarly, Figure 10 is the total survivability star plot of the Corvette and Destroyer design studies, compared to Frigate Variant 1, against which again the results were normalised.

Finally, the total survivability star plot of the two auxiliary ship designs is illustrated in Figure 11. On this occasion the survivability results of these two design studies have been normalised with respect to the worst performing design, rather than a baseline design, as explained in Section 3.2 (e) and detailed in [10].

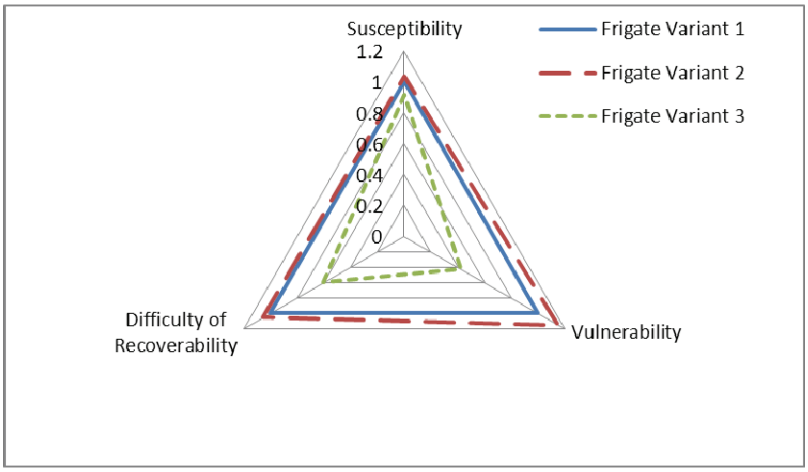


Figure 9: Normalised Star Plot of Survivability for the Three Frigate Design Variants

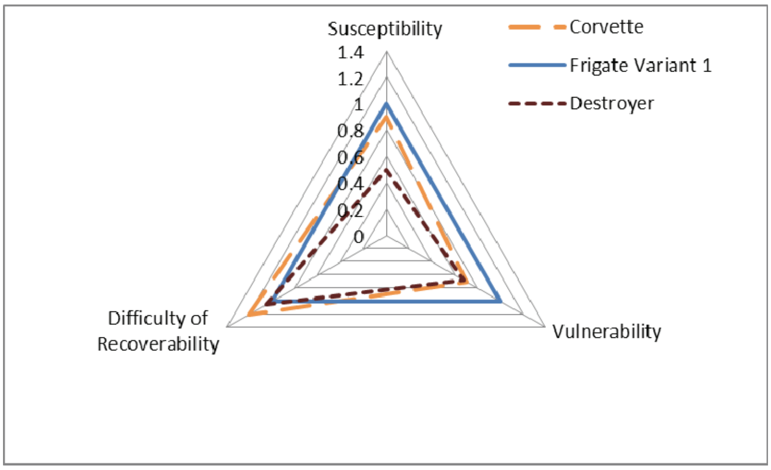


Figure 10: Normalised Star Plot of Survivability for the Corvette, Baseline Frigate and Destroyer

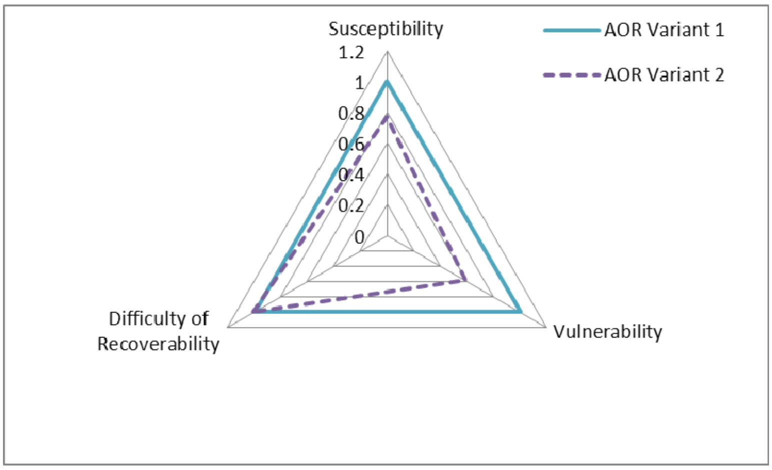


Figure 11: Normalised Star Plot of Survivability for the Two AOR Variants

6. DISCUSSION

The results summarised in Section 5 and Figures 9, 10 and 11 depend on a large number of factors, leading to a significant set of conclusions that were drawn from the analysis of the results through out the project [10]. This section briefly summarises the main conclusions on the three survivability constituents. Also included is a summary of the achievements of this research and the degree to which the objectives of the research were met.

6.1 RESULTS ANALYSIS OF SURVIVABILITY

Regarding susceptibility reduction, the beneficial effect of features such as the application of a 7^{o} slope to superstructure sides, the placing of as much likely microgeometry as possible behind bulwarks and the avoidance of corner reflector, as well as the effect of a smaller hull were confirmed. In addition, the dominant effect observed, on susceptibility performance, was that of the extent of the defensive (AAW in this case) capability of the naval ship.

The main observations concerning vulnerability performance can be summarised as: Trimarans generally provide reduced vulnerability due to the protection provided by the side hulls, although trimarans are more vulnerable than equivalent monohulls at the narrow forward and aft ends; equipment located deep in the hull is less vulnerable to abovewater attack; increasing ship size tends to reduce vulnerability, duplication of identical systems significantly reduces vulnerability (provided that the redundant systems are reasonably separated); improved system layout decreases vulnerability (provided, for example, through the large box structure and associated DC deck and weatherdeck wide beam in a trimaran); and the protection of certain high value items by secondary compartments reduces system vulnerability.

With respect to recoverability, various conclusions were derived. For example, the dominant impact identified was on the recoverability performance of the number of items damaged, and therefore unavailable post-hit, requiring repair. This, however, raises concerns regarding the identification of the boundary between vulnerability and recoverability, since the extent of damage is directly related to vulnerability. However, the extent of post-hit repair works necessary, directly related to recoverability, is also dependent upon the extent of damage. In addition, the effect of the access arrangements on the damaged areas was also identified as significant. Furthermore, the positive effect of greater ship size (but also zone size) on recoverability was observed. This is attributed to the increased post attack availability of items and systems in larger ships, due to the inherently more extensive vulnerability reduction features of such larger ships.

6.2 RESEARCH REVIEW

It is widely accepted that naval ship design has shifted from achieving the technically best to just obtaining affordable designs [50]. This is a result of a combination of various factors, such as the above-inflation increase in UPC of all military equipment [51] and the declining defence budgets, in western navies in particular. This has then led to a gradual reduction in the number of ships of most western navies. In response to these developments, survivability features, whose performance is difficult to quantify, become hard to justify and thus present an apparently attractive area for cost cutting. It has been argued that such attitudes could lead to unbalanced and ineffective ship designs [17], especially when considering the increase in magnitude and variety of threats that warships currently face. Furthermore, this worrying situation is further exacerbated by the decreasing number of warships in a given fleet.

It is widely recognised that the time and resources expended during the concept phase are minimal in comparison to the entire project, despite most major decisions and trade off studies, which will define the final product, being taken in this phase. Given its importance to mission effectiveness, the ability to include survivability assessment in preliminary naval ship design is seen to be highly desirable. Since most warships are described as 'architecture limited' [52], it is seen to be beneficial that any survivability assessment method is structured so that it can draw on a fully integrated and configurationally orientated preliminary design description of a new ship concept.

Susceptibility and vulnerability assessment techniques, applicable in preliminary ship design, exist and have been utilised in actual warship design projects [53] [54]. However, there is no recoverability assessment method, available in open sources, appropriate to the early formative stages of naval ship design. Therefore, a new recoverability assessment approach has been developed. It has been shown to work on the basis of developing a number of recoverability related Performance Measures, together with an appropriate weighting scheme. The proposed approach links recoverability assessment to preliminary architectural ship design, which is characterised by limited detailed design descriptions. In addition, the approach facilitates the backtracking of the assessment results and identification of features undesirable with respect to survivability, which could then be readily altered given the preliminary nature of the ship designs.

7. CONCLUSIONS

7.1 GENERAL CONCLUSIONS

The proposed design approach has been shown to be able to identify the principal survivability drivers for several ship types and hullform configurations. In addition, it is able to investigate the effect of factors, such as ship internal configuration, hull configuration and ship size, on survivability performance. Moreover, by assessing all three survivability constituents equally, a balance between survivability features may confidently be attempted. The fact that the proposed survivability assessment approach is linked to an architecturally orientated preliminary design approach allows the investigation of alternative ship design styles, as well as specific survivability features, in the earliest design stages. During these stages, ship designs are amenable to modifications, which would be expensive or even infeasible in the later design stages.

Finally, the quantification of survivability can be used to justify enhancing a design option's survivability features. This would then discourage arbitrary cost cutting of features significant in ensuring adequate survivability in naval vessels and mitigating loss of life to their personnel at sea. Moreover, through the quantification of survivability, the proposed approach encourages more meaningful performance-based (rather than prescriptive, feature-based) trade-off analyses for a ship design project. Thus, with survivability analysis commencing at the early design stages, survivability assessment can be an integral part of the vital initial design process [21].

7.2 FUTURE WORK

It is considered that the proposed approach has been substantially demonstrated [10], however, a number of issues are worth being addressed before the proposed survivability assessment approach could be considered mature. These include :-

- A better understanding of the cost of ship survivability;
- The appropriateness of the weighting scheme adopted;
- The modelling of secondary damage;
- The inclusion of multiple and varying threats;
- The correct identification of the boundary between vulnerability and recoverability.

Despite a significant amount of further work suggested, it is considered that the research to date has contributed to advancing knowledge of what is possible to be taken into account in the earliest stages of the design process of naval vessels.

8. ACKNOWLEDGEMENTS

Funding for this project was provided by EPSRC (CASE studentship) with sponsorship by Dstl and both are gratefully acknowledged, particularly the advice and guidance from Dr. J.S. Thornton as the Dstl sponsoring officer. The assistance provided by the staff of the Department of Mechanical Engineering of UCL, and in particular by Dr R. J. Pawling, as well as by Lt. Cdr. T. Day, RN (Rtd.), Dr K. White and Mr S.J. Parry, all of whom belong to the Maritime Integrated Survivability team (part of the Maritime Systems Engineering Group in Naval Systems Department) of Dstl, is acknowledged. Furthermore, the advice of 1st Lt. P. Fonseca, Portuguese Navy, and Cdr. J. Sutcliffe, RN, Lt. Cdr. J. Mant, RN (Rtd), Lt. Cdr. J. Boughton, RN, Lt. Cdr. K. Hood, RN, Lt. Cdr. B. Kadinopoulos, RN, Lt. Cdr. T. O'Brien, RN and Lt. M. Koheeallee, RN, who all provided insights on survivability related features and procedures onboard RN and Portugese Navy vessels, is also acknowledged.

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APPENDIX – Tables 4 and 6

Table 4: Scheme for Compiling the Recoverability Performance Measures Matrix of a Combatant Concept Design (with example numerics)

Column		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
				WT Section	**A_1**	**A_2**	**B_1**	**B_2**	**C_1**	**C_2**	**…**							
Group description		***PM cat.***	***PM***	***Weighting***								***Sum***	***Normalised with respect to baseline***	***Weighted***	***Group Sum***	***Normalised with respect to baseline***	***Group Weighting***	***Weighted***
FLOAT		Cat. 1 PMs	$PM_{1.1}$	7	55.1	0.24	44.5	0.63	33.0	1.33	…	27.9	1.0	7.0				
			$PM_{1.2}$	4	5.0	0.02	4.0	0.06	3.0	0.12	…	2.4	1.0	4.0	90.0	1.0	10.0	10.0
			$PM_{1....}$	…	…	…	…	…	…	…	…	…	…	…				
Recovery Support		Cat. 2 PMs	$PM_{2.1}$															
			$PM_{2.2}$															
			$PM_{2....}$															
MOVE	**Move System**	Cat. 3 PMs	$PM_{3.1.1}$															
			$PM_{3.2.1}$															
			$PM_{3.3....}$															
FIGHT	**Naval Gun System**	Cat. 3 PMs	$PM_{3.1.2}$															
			$PM_{3.2.2}$															
			$PM_{3.3....}$															
	ASM System	Cat. 3 PMs	$PM_{3.1.3}$															
			$PM_{3.2.3}$															
			$PM_{3.3....}$															
	Aft SAM System	Cat. 3 PMs	$PM_{3.1.4}$															
			$PM_{3.2.4}$															
			$PM_{3.3....}$															
	Fwd SAM System	Cat. 3 PMs	$PM_{3.1.5}$															
			$PM_{3.2.5}$															
			$PM_{3.3....}$															
	Helicopter System	Cat. 3 PMs	$PM_{3.1.6}$															
			$PM_{3.2.6}$															
			$PM_{3.3....}$															
Total Score																		

Table 6: Scheme for Compiling the Recoverability Performance Measures Matrix of a Replenishment Ship Concept Design (with example numerics)

	Column	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
				WT Section	**A_1**	**A_2**	**B_1**	**B_2**	**C_1**	**C_2**	**…**	***Sum***	***Normalised wrt worst performing***	***Weighted***	***Group Sum***	***Normalised wrt worst performing***	***Group Weighting***	***Weighted***
	Group description	***PM cat.***	***PM***	***Weighting***														
	FLOAT	Cat. 1 PMs	$PM_{1.1}$	4	94.0	0.26	82.1	0.63	82.1	1.38	…	82.2	1.0	4.0				
			$PM_{1.2}$	4	7.5	0.02	6.5	0.05	6.5	0.11	…	6.5	1.0	4.0	50.6	0.69	10.0	6.9
			$PM_{1....}$	…	…	…	…	…	…	…	…	…	…	…				
	Recovery Support	Cat. 2 PMs	$PM_{2.1}$															
			$PM_{2.2}$															
			$PM_{2....}$															
MOVE	**Move System**	Cat. 3 PMs	$PM_{3.1.1}$															
			$PM_{3.2.1}$															
			$PM_{3.3....}$															
FIGHT	**Ability to RAS AVCAT**	Cat. 3 PMs	$PM_{3.1.2}$															
			$PM_{3.2.2}$															
			$PM_{3.3....}$															
	Ability to RAS dieso	Cat. 3 PMs	$PM_{3.1.3}$															
			$PM_{3.2.3}$															
			$PM_{3.3....}$															
	Ability to RAS dry stores	Cat. 3 PMs	$PM_{3.1.4}$															
			$PM_{3.2.4}$															
			$PM_{3.3....}$															
	Ability to RAS ordnance	Cat. 3 PMs	$PM_{3.1.5}$															
			$PM_{3.2.5}$															
			$PM_{3.3....}$															
	Aviation support	Cat. 3 PMs	$PM_{3.1.6}$															
			$PM_{3.2.6}$															
			$PM_{3.3....}$															
	CIWS	Cat. 3 PMs	$PM_{3.1.7}$															
			$PM_{3.2.7}$															
			$PM_{3.3....}$															
																	Total Score	