Appendices

Appendix 1: Margins in Ship Design

The choice of margins plays a critical role in preliminary design; therefore, a brief literature review of the importance and types of margins is presented here.

A margins philosophy should be decided on before the commencement of design (Heather 1990). Margins are applied to variables such as weight, VCG, propulsion power, electric load, air conditioning, (Brown 1986a; Heather 1990) and space (space margins may also be required in a particular location (Brown 1987)), and are allocated across the various weight or functional groups (Andrews 1987). The importance of margin selection is obvious when considering the fact that the resultant ship size, cost and performance are highly dependent on them (Brown and Andrews 1980; Garzke and Kerr 1985). For example, the ability of a warship to be updated and fitted with a new weapon system during the course of its commission is dependent upon reasonable margin selection (Brown and Andrews 1980; Brown 1987). The choice of margin philosophy should reflect upon the type of design process and the stage in design (Section 2.1.2).

There are generally considered to be three types of margins:

- Design (and construction) margins: which are separately allocated to the weight or functional groups describing the ship and are closely linked to design novelty; they allow for errors, uncertainties, omissions and future design changes (Andrews and Brown 1982; Brown 1986a; Heather 1990; Andrews and Pawling 2007; UCL 2010a).
- Board margins: to allow for future payload additions resulting from requirements changes (Andrews and Brown 1982; Brown 1986a; Andrews 1987; Andrews and Pawling 2007; UCL 2010a). Andrews et al (2012b) suggests that applying board margin to specific areas (rather than applying it ship wide, which is the current practice) would result to significant ship size reductions, therefore allowing for specific capability enhancement without greatly effecting overall ship size.
- Growth margins: to allow for through life accretion and deliberate changes (Andrews and Brown 1982; Brown 1986a; Andrews 1987; Heather 1990; Andrews and Pawling 2007; UCL 2010a).

In Tables II and III of (Heather 1990), the author suggests typical margin values used during different design stages for the various areas where they are applicable. Cimino and Filipopoulos (2001) also give guidance on margins with respect to degree of novelty and risk inherent in the design from a USN perspective (Figure 4, Tables 3, 4 and 5 of the reference).

Appendix 2: Ship Type Design Drivers

This appendix summarises views from published literature of the major design drivers of various presently common naval ship types. Design drivers of combatants, with both conventional and unconventional hull configurations, but also replenishment ships are investigated.

A2.1 Combatants

It is well accepted that frigates and destroyers are the most common type of warship for most respectable navies with blue water aspirations (Brown and Andrews 1980; Andrews et al 2004). Therefore it is common to test new developments on such ships and so it is important to look at what drives their design according to the extensive literature.

In the past, most warships were weight limited but this has now changed to space limited (Andrews 1984; Brown and Tupper 1989) and more specifically upper deck limited, since there must be enough space for the weapons and sensors to function (Brown 1986a; Gale 2003). Since beam is set by stability considerations, the only free dimension relevant to upperdeck layout is length (Brown 1987). The major factors driving the length of frigate (and other combatant) type ships are: weapon location (for good arcs of fire and low vulnerability), sensor location and required clearances, flight deck and hangar arrangement, bridge location, boat operation, size and access of superstructure (a small superstructure minimises wind loading (Andrews and Brown 1982; Brown 1987) and RCS (Brown 1986a; Heather 1990) and avoids structural problems (Brown 1986a; Crow 2001) but causes access problems (Crow 2001)), mast location, RAS arrangement (amidships of combatant and replenishment ship should be adjacent, however, due to lack of space it is common for smaller combatants to position their RAS rigs forward of the superstructure or on the flight deck (Chislett 1972) which could, however, lead to spilt dieso on the flight deck (Manley 2012)), mooring arrangement, etc. (UCL 2001). Different priorities are given to different combatants; for example in an ASW combatant the flight deck location is of prime prominence while in an AAW combatant, clear arcs of fire (Brown 1987). The upper deck arrangement is strongly linked to the internal configuration through the location of machinery compartments and their corresponding uptakes and downtakes (Brown 1987) which should be conveniently located so that their physical position and exhaust plumes do not affect operations (Heather 1990). The above is summarised in Figure A1.

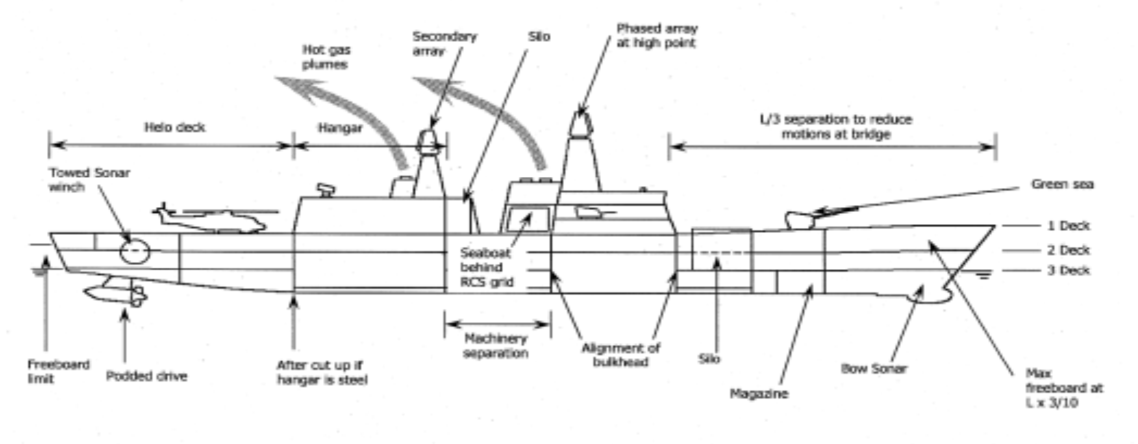


Figure A1: Frigate Layout Consideration (Andrews 2003)

Another important aspect of warship design is aesthetic consideration (both for deterrent effect and because it is a country's representative), which, although not as important as weapon and sensor integration, should be addresses early in the design, when changes can be easily incorporated (Donnelly 1985; Heather 1990). From the above it is clear that the minimum length of a frigate (and other combatants) is set by the upper deck arrangements; since there is no defined upper limit, factors such as seakeeping, manoeuvring, structural strength, speed and cost should be considered (Andrews and Brown 1982).

Helicopters operations are limited by the sea state and the resulting ship's vertical and rolling motions (Lloyd and Hanson 1985; Brown 1986a), while replenishing ordnance is considered the most demanding and weather limited activity (Lloyd and Hanson 1985). The optimum location for aviation facilities in this regard is at amidships where motions are kept to a minimum and the helicopters operational effectiveness is enhanced (Lloyd and Hanson 1985; Brown 1991). However, such a location introduces further hazards due to obstructions aft of the flight deck (Lloyd and Hanson 1985; Gates 2005), e.g.: machinery uptakes and downtakes (UCL 2001; Andrews and Pawling 2006a), which might, however, be overcome with the adoption of IFEP (UCL 2001) promoting widely separated machinery (Brown 1993). Most pilots, however, prefer an aft flight deck location for safe helicopter operations (Cooper et al 2007).

Due mainly to the link between machinery location and upper deck design created by the engines uptakes and downtakes, Brown (1987) argues that the key to a frigates internal layout is the arrangement of the upper deck, described above. However, advancements in IFEP technology have led to further choice in arrangements through widely separated machinery compartments, which also reduce vulnerability (Brown 1987; Linklater 2012) and may be relevant for the complex operating profile of a warship (Cooper et al 2007). IFEP also has the advantage of removing the need for long shafts (Andrews et al 2004; Linklater 2012) with possibly the use of pods enabling reduced internal space requirements (Andrews and Pawling 2007; Linklater 2012), as well as improved manoeuvrability and propeller flow, to recover lost machinery efficiency of IFEP systems (Andrews and Pawling 2007). However, other disadvantages such as a large concentration of weight on the after end of the ship (Andrews et al 2004; Linklater 2012) as well as the uncertain shock performance of pods (Linklater 2012) are problematic. Some compartments are restricted to specific locations, e.g. bridge (UCL 2001); some are restricted by environmental constraints, such that working and living spaces ought to be sited at areas of low motions and noise (although it has been observed that with smaller combatants such as corvettes, the lower priority of such spaces compared to operational spaces and equipment have led to their location in uncomfortable areas, often adjacent to machinery spaces (Usher and Dorey 1982)); and others are restricted by adjacency requirements. Such compartments need to be considered at the outset of the layout design in order to minimise compromises (Brown 1986a). Further layout constraints can be introduced by the hydrodynamic shape of the hull (Brown 1987). Features such as number of decks, superstructure size and arrangement, access philosophy (two side passageways for better personnel flow and compartment protection versus a centreline passageway for reduced volume and easier access (Ferreiro and Stonehouse 1994)) and zoning can govern the ships internal configuration (Brown 1987; Heather 1990). Other aspects such as modularity (Andrews and Pawling 2006a), adaptability and versatility (Brown 1993), ease of installation, operation and maintenance and cost factors also affect the configuration of a combatant (Brown 1987).

Another factor linking the upper deck and internal configuration of a combatant, which should be investigated at the initial design stages, concurrently with layout development, is structural continuity (Brown 1987; Crow 2001). Structural continuity determines bulkhead location (bulkheads must be sited at superstructure ends, heavy equipment/masts locations and at the after cut-up (Chalmers 1993a; Crow 2001)), introducing further configurational constraints (Brown 1987) and interacting with damage stability considerations (Gale 2003). Add to this, penetrations, such as vertical access, uptakes and downtakes and removal routes, must be grouped together in a lengthwise arrangement (preferable if smaller penetrations are placed in the shadow of larger ones) in order to minimise the ineffective structure (Brown and Tupper 1989; Chalmers 1993a). This can then make side passageways undesirable (Chalmers 1993a). Further constraints are imposed by the fact that the upper (strength) deck and inner bottom must by structurally continuous in the longitudinal direction. It is generally considered that concentrating the majority of the volume in the hull (with a minimal superstructure) leads to a more efficient structural design (Chalmers 1993a).

In conclusion, Andrews et al (2004) identified the choice of the propulsion and combat systems (the fight and move groups of the functional description) as normally the main preliminary design determinants for combatants, which drive the size, style and cost of the ship. Brown (1993) separated the necessary decisions to be made by the designer into first level, mainly concerning upper deck arrangement and second level, mainly concerning internal configuration. Such issues must be considered early in the design (Brown 1986a; Andrews and Dicks 1997) and a profile sketch such as the one in Figure A1 is a good starting point for the design of a combatant (Brown 1986a). It is clear that the main design drivers of frigate (and other combatant) type ships are related to its configuration and must be investigated at the commencement of design, which is seen to justify the (fully integrated, architecturally orientated) DBB approach to preliminary ship design (Andrews 2003).

A2.2 Trimaran Combatants

As previously noted, the concept phase of ship design is divergent and imaginative and therefore, a large number of alternative designs should be considered, including trimarans, SWATHs, etc. (Andrews et al 2006). Since modern warfare has increased emphasis on littoral operations where asymmetric threats are present, there is a need for fast, adaptable and survivable warships (Andrews and Pawling 2006a). Trimarans present a promising solution to such requirements proposed only recently (Andrews 2004) and so additional design drivers and features of such hull configurations will be discussed as it is seen to be a prime candidate in considering alternative ship configurations.

A trimaran is essentially a long narrow monohull (L/B>14) with the addition of two small side hulls connected by a box structure (Andrews and Hall 1995; Andrews 2004). This hull configuration was initially sought due to its powering performance (reduced wave making resistance) arising from the slender main hull (Andrews and Zhang 1995; Andrews 2004). The loss of transverse stability in then compensated by the addition of the much smaller side hulls (3-5% of the total displacement per side hull), therefore decoupling the two areas of powering and stability (Andrews and Zhang 1995; Andrews 2004). It has been suggested that the powering advantages of a trimaran would lead to smaller machinery units and decreased fuel consumption which would lead to a smaller and cheaper ship (Andrews and Hall 1995).

In such ship configurations, architecture plays an even more prominent role, mainly due to the large box structure connecting the three hulls, therefore, being the main design driver which should be addressed from the start (Andrews and Dicks 1997; Andrews et al 2006). Due to the large surface area of the upper deck (larger overall beam), the designer has a wider choice of arrangements (e.g.: it is easier to locate the aviation facilities amidships) (Andrews and Zhang 1995; Andrews and Pawling 2008). Also, since stability is decoupled from powering considerations, it is possible to locate heavy items higher up in the ship for better effectiveness, e.g.: radars (Andrews 2004). In addition, the large box structure can be utilised to better arrange the main deck and improve layout for survivability, operability, modularity, personnel flow, etc. (Andrews and Hall 1995; Andrews and Pawling 2008). Thus the arrangement of accommodation can be made significantly easier by locating the spaces in the shorter and beamier central part of the ship where low motions occur (Andrews and Pawling 2006a). In general, it can be said that the increased number of parameters (comparatively to a monohull) increase the significance of the architectural design (Andrews et al 2012a).

Trimarans present clear advantages in upper deck and main deck layout, as well as powering and therefore, these areas constitute the main design drivers such ships. Further advantages include the protection provided by the side hulls to attacks from torpedoes and missiles, the fact that if damaged, the side hulls can be ballasted in order to heel the ship away from the damaged part, good directional stability, improved seakeeping (Andrews and Zhang 1995; Andrews and Pawling 2008). These advantages are enhanced by the fact that a trimaran is in many ways a variant of a monohull (in contrast to the more radical SWATH and catamaran) therefore considerably reducing development risks (Andrews and Hall 1995). However, trimarans have certain disadvantages such as the low main hull beam not readily facilitating a double shaft arrangement (although this could be overcome with the inclusion of prime movers in the side hulls, which would also improve manoeuvrability but introduce further difficulties arising from the very low beam and volume of the side hulls); the requirement of a 3.5m minimum air gap to the underside of the box structure (arising from requirements to minimise slamming); the air gap in combination with the slender main and side hulls can lead to many unusable spaces leading to excessive volume; the centrally located box structure and high freeboard introduce difficulties in boat handling; and the relatively high structural weight fraction (Andrews and Zhang 1995; Andrews 2004). Figure A2 demonstrates a qualitative assessment of different hullform types as perceived by Andrews (2004).

Aspects (Table (1)) \ Ship Types	Monohull	Catamaran	ACV	SES	Hydrofoil	SWATH	HYSWAS	WIG	Trimaran
Speed, Power and Endurance	Good	Good[1]	V Good[2]	Good	V Good[2]	Good	Good	V Good	Good
Space and layout	Good	Good	Ave	Good	Poor	V Good	Poor	Poor	V Good
Structural design and weight	V Good	Ave	Poor	Poor	V Poor	Ave	Poor	V Poor	Good
Stability	Good	Good	Good	Good	Good[3]	Good	Good	Poor	V Good
Manoeuvrability	Good	Ave	Poor	Good	Good	Ave	Good	Poor	Good
Noise, Radar & Magnetic Signature	Good	Ave	Good	Good	Good	V Good	Good	Good	V Good
Weapon placement & effectiveness	Good	Ave	Ave	Ave	Poor	Good	Ave	Poor	V Good
Construction costs and build time	V Good	High	V High	High	V High	Good	High	V High	Good
Through life costs	Good	Ave	V High	High	V High	Ave	High	V High	V Good

Notes.
1. But bad in deep ocean seaway
2. Very fast but limited to hull borne (slow) in seaway and endurance poor (fuel weight)
3. Very good hull borne but foil borne degraded by wave effects in deep ocean.

Figure A2: A Qualitative Assessment of Different Hull Forms (Andrews 2004)

Despite the disadvantages, trimarans present a promising and flexible configuration to meet the requirements of the future as the scope in selecting the wider range of hull dimensions for such ships means they can be more directly driven by functional needs without the limitation in dimension choices applying to monohulls (Andrews and Hall 1995). This should mean that the designer is freer to modify the particular design to achieve a better solution (Andrews and Hall 1995).

A2.3 Replenishment Ships

The need for global military presence despite the declining defence budgets and fleet sizes, combined with new IMO regulations, have lead many navies to a requirement for improved underway replenishment capabilities (Bricknell and Vedlog 2007; Andrews and Pawling 2007). Furthermore, the RAS ability of RN warships was essential during the Falklands conflict (Manley 2012). Some navies have even sought to combine RAS requirements with sea lift, intervention and sea basing as a more affordable solution (Cooper et al 2007; Scott 2010). Replenishment ships are required to provide fuel, lubricants, dry stores and ordnance to the fleet (Bricknell and Vedlog 2007), so a commercial based ship solution can be largely adopted (Cooper et al 2007). However, there are a number of factors differentiating such ships from commercial cargo ships, such as the ability to keep up with the fleet (requiring speeds of at least 18kts), special replenishing facilities while underway, good manoeuvrability, aviation capability, etc. (Bricknell and Vedlog 2007; Cooper et al 2007).

Chislett (1972) provides a brief historical account for the needs and techniques of RAS. RAS operations are highly dependent on the sea state and resulting pitch motions (Bricknell et al 2006; Bricknell and Vedlog 2007). Bricknell and Vedlog (2007) suggested that in order to deliver fuel in sea state 7 and stores in sea state 6, the minimum required length of the ship is 200m. A significant driver of such ships arises from the required aviation capability (Cooper et al 2007); a single spot flight deck and hangar for maintenance could require as much as 55m of length (Bricknell et al 2006). For more extensive aviation requirements, such as the operability of two Chinooks in the Dutch JSS, the aviation footprint (combined length of flight deck and hangar) can account for up to 95% of the ship's length (Scott 2010). An additional important design driver is the efficient arrangement of the ship's cargo; for example hazardous cargo should be separated, RAS operations with ordnance require short routes (Andrews and Pawling 2007; Scott 2010), IFEP could assist in separating the main machinery compartment forward and aft, therefore locating the stores and tanks in the wide central part of the ship (this also minimises routes from stores/tanks to amidships positioned RAS rigs and minimises ballast requirements when operating in light conditions) (Andrews and Pawling 2007), the use of podded propulsors requires reduced internal volume, therefore providing more storage and tankage space (Andrews and Pawling 2007). Once again, the upperdeck arrangement of such ships is linked to the internal arrangement through the location of machinery spaces and their corresponding uptakes and downkakes, in addition to store lifts (Andrews and Pawling 2007).

As a general rule, Cooper et al (2007) suggests that the main design drivers for such ships are the aviation requirements, the accommodation requirements and cargo storage. Although RAS rig location is vital for the efficient operation of replenishment ships, their placement is not usually a design driver due to the large abundant deck area above the cargo tanks (Cooper et al 2007). The above are summarised in Figure A3.

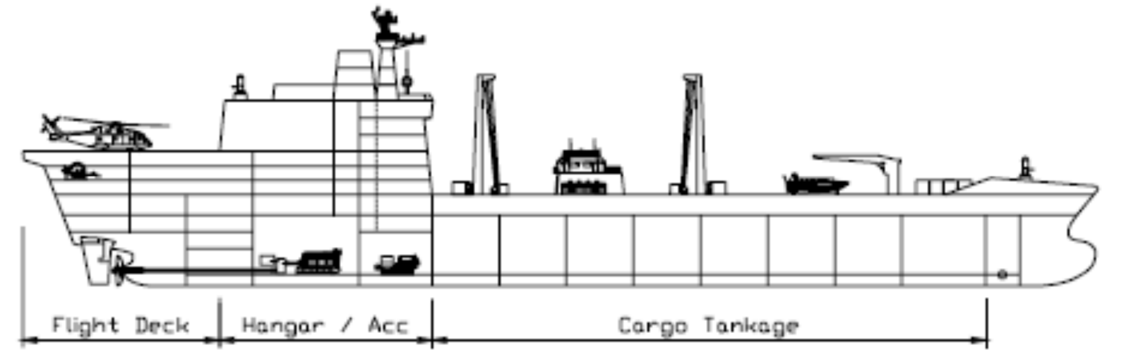


Figure A3: Fleet Tanker Size Drivers (Cooper et al 2007)

Replenishment ships are generally considered to be volume limited (Gale 2003), unless they are exclusively tankers (which are displacement tankers) in which case they would be weight limited (Rawson and Tupper 2001).

Appendix 3: Survivability Definitions

NATO (2003a) – See Figure 3.1 in Section 3.1.

Ashe et al (2006) – "Survivability is the capability of a naval ship to avoid and/or withstand a man made hostile environment while performing its mission; the three main elements of survivability are: (1) susceptibility, the ability to avoid detection; (2) vulnerability, the ability to withstand a hit; and (3) recoverability, the ability to reconfigure and restore the damaged systems after a hit."

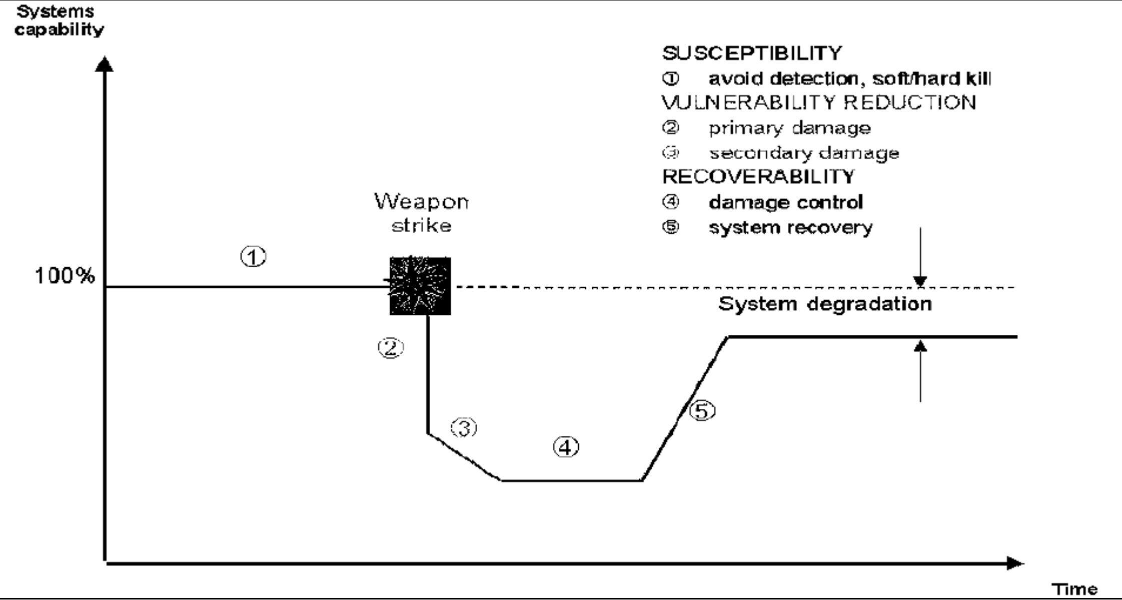


Figure A4: The Three Elements of Survivability (Ashe et al 2006)

Bain (2006) –

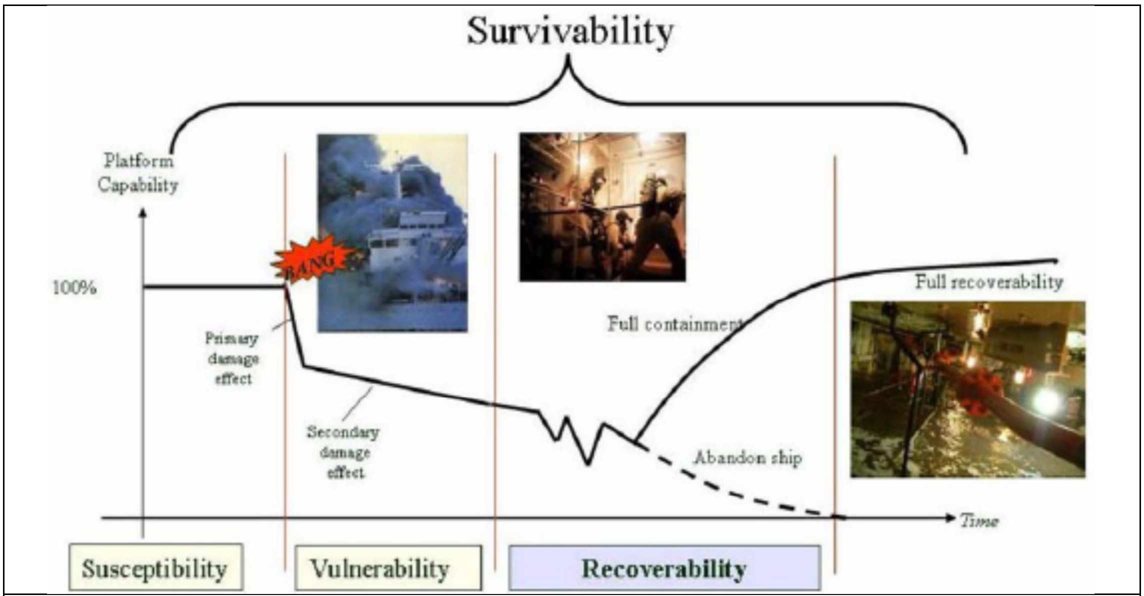


Figure A5: Platform Survivability (Bain 2006)

"Recoverability is specifically concerned with restoring a platform's capability against time and is defined as: 'The ability to recover capability, partially or fully, within a specified timescale and to sustain that recovered capability for a given period'."

Ball and Calvano (1994) – "We define surface ship combat survivability as "the capability of a surface ship to avoid and/or withstand a manmade hostile environment while performing its mission"… The inability of a ship to avoid the sensors, weapons and weapons effects of that man-made hostile environment is called susceptibility. In addressing the other half of that key phrase, the inability of the ship to withstand the effects of the hostile environment is called vulnerability."

Barnett (1998) – "A ships ability to survive and remain combat capable depends on three related factors: susceptibility, the ship's ability to avoid detection, seduce weapons from vulnerable areas, or kill incoming threats in order to avoid being hit; vulnerability, the ability to minimise damage to the ship, its systems, and its crew; and, recoverability, the ability to rapidly restore critical ship functions that will sustain warfighting capability."

Belcher (2008) – "Survivability means the ability to survive a certain situation… However, in the naval context… it is not just surviving a situation; it also considers how one got into the situation in the first place, and how one will behave well after the situation is resolved… Given a particular threat, the survivability of a ship depends on its susceptibility to the threat and its vulnerability to the effects of the threat… The basic premise of susceptibility is that it is better to avoid a hit than to endure one, that it is better to hide than harden. Any steps taken to reduce the probability of being hit fall within the susceptibility regime… Vulnerability is a measure of how serious the effect of a hit will be, and more importantly, what will be the capabilities of the ship afterwards."

Cerminara and Kotacka (1990) – "Survivability is the capability of a weapon system to continue to carry out its designated mission(s) in a combat threat environment. The two basic elements of survivability are susceptibility and vulnerability. Susceptibility is a combination of factors that determine the probability of a hit by a given threat. It implies "don't be seen" and "don't get hit" and deals with threat avoidance and includes concealment, countermeasures, signature management, etc. Vulnerability is the extent of degradation of a system after having been subjected to combat threat(s). Vulnerability implies "don't get penetrated" and "don't get destroyed" and deals with such specific design principles as damage resistance, damage tolerance, and damage control and recovery. Damage resistance includes hardening and shielding. Damage tolerance includes separation, redundancy, as well as the concept of hull, mechanical and electrical enclaving. Damage control and recovery in broad terms includes damage prevention, system reconfiguration and repair, as well as such advanced concepts as damage control management systems."

Harney (2010) – "Survivability is generally considered to have two components: susceptibility (the ability of the enemy to detect, localize, engage, and hit a target) and vulnerability (the degree to which a hit can cause serious damage to the target). An arguable third component – recoverability – can be incorporated into vulnerability."

Heather (1990) – "Susceptibility is the liability of a ship to be detected by an enemy, therefore opening it up to attack. This will be a function of low signatures and control of radio/radar/sonar emissions. Vulnerability is the liability of a ship to be damaged by a weapon and the seriousness of the consequences of the attack. Survivability is the combination of susceptibility and vulnerability giving the overall capability of the ship to avoid or resists the effects of enemy weapons."

Martin (2007) – "Susceptibility: a measure of the ships capacity to avoid being hit. It reflects subjects like signature control (to avoid being detected), decoy effectiveness (to avoid being targeted), and hard kill defensive measures to avoid being hit when targeted. Vulnerability: a measure of the ship's inherent capability to withstand damage in the immediate aftermath of a hit or nearby detonation. Typically this is addressed through concentration of critical equipment, duplication and separation as well as blast management, armour and shock protection. Recoverability: a measure of the ships capacity to limit progressive damage (fire/flood) and restore capability. It addresses issues such as crew numbers and skills, automated systems, damage control equipment and spares policy."

MOD (2001) – In addition to ANEP 43 (NATO 2003a) survivability definitions, "Reference will also be made to two additional terms:

- "Functional Survivability" – probability of a particular function or system surviving a damaging hit, i.e. (1 – Vulnerability), so a system that is 20% vulnerable will have a functional survivability of 80%.
- "Basic Survivability" – the probability of the vessel or platform retaining some level of function after damage (e.g. for a surface ship the vessel is still afloat and stable)."

Papanikolaou and Boulougouris (1998) – "For naval ships survivability is the capability to continue to carry out their missions in the combat lethal environment. This is a function of their ability to prevent the enemy from detecting, classifying, targeting, attacking or hitting them. The inability to "intercept" any of the above threats is a measure of their susceptibility... the degree of impairment she suffers in case of damage characterizes her vulnerability.' Boulougouris and Papanikolaou (2012) recognised that 'the primary weapon effects (i.e. explosion and fragments) degrades instantly the operating level while the secondary effects (i.e. fire, flooding and system and structure failures) degrades it less rapidly but still significantly. Only damage control procedures may restore partially ship's capability. These constitute the *recoverability*. By definition recoverability is mainly an operational aspect relying mainly on the sufficient training of the crew although it may still pose several requirements to the designer."

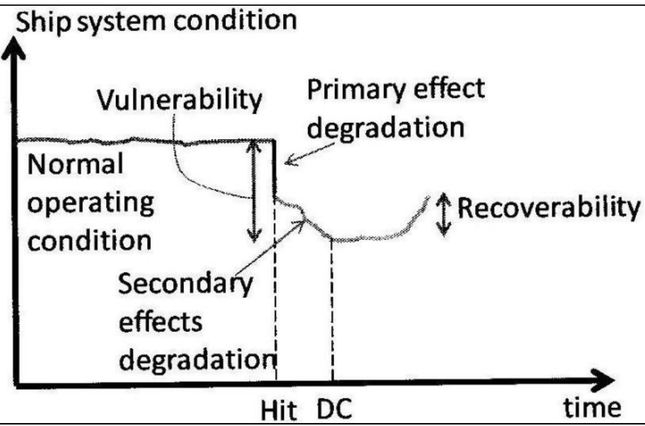


Figure A6: Visualisation of Vulnerability and Recoverability (Boulougouris and Papanikolaou 2012)

Petersen (2006) – "Survivability of a naval ship must be regarded as its ability to withstand a defined weapon threat and to maintain at least a basic degree of safety and operability of the ship. Survivability is more or less threatened by:

- Loss of global strength of hull structure
- Loss of buoyancy and/or stability
- Loss of manoeuvrability
- Fire in the ship, and ineffective fire protection or firefighting capability
- Direct destruction of machinery, equipment, or control systems
- Direct destruction of weapons and sensors
- Threats to the physical conditions of the crew"

Phillips (1998) – "Survivability is what you can design into the ship: techniques of construction and use of materials. Vulnerability relates to where you put the ship: the Force Commanders' decision."

Reese et al (1998) – "Combat survivability is the ability to avoid or withstand a man-made hostile environment, taking into consideration the sea conditions in which the ship must operate… The inability to avoid a man-made hostile environment is the ship's susceptibility, quantified by the probability of being hit. The inability to withstand the hostile environment is vulnerability, quantified by the conditional probability of being killed if hit… Survivability is the… product of the probability of being hit (susceptibility) and the probability of being killed if hit (vulnerability). The navy has recently defined another element, recoverability, which involves crew actions in reconfiguring and restoring damaged systems to enable the ship to carry out its missions under damaged conditions."

Richards et al (2008) – "Survivability is the ability of a system to minimize the impact of a finite-duration disturbance on value delivery. Survivability may be achieved through either (1) the reduction of the likelihood or magnitude of a disturbance, Type I survivability, or (2) the satisfaction of a minimally acceptable level of value delivery during and after a finite disturbance, Type II survivability."

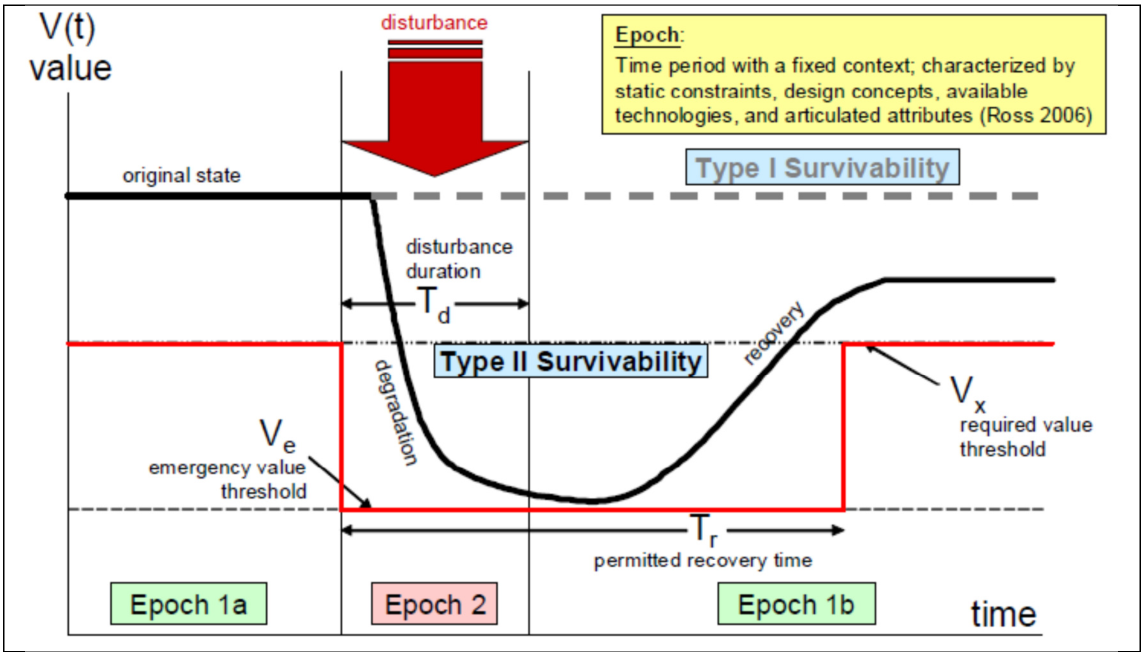


Figure A7: Definition of Survivability (Richards et al 2008)

Robb et al (2010) – "In general survivability consists of three main areas; Susceptibility, Vulnerability and Recoverability. The following commonly used definitions are referenced from ANEP 43.

- Susceptibility: avoidance of being hit, which includes platform signatures, and hard and soft kill measures.
- Vulnerability: intrinsic robustness to minimise the damage should a hit occur.
- Recoverability: ability to repair damage and recover capability."

Said (1995) – "Historically, ship survivability has been defined as: "The capability of a ship and its shipboard systems to avoid and withstand a weapons effects environment without sustaining impairment of their ability to accomplish designated missions"… better expressed as the product of three major elements… Susceptibility refers to the inability of a ship to avoid being damaged in the pursuit of its mission and to its probability of being hit… dependent on three factors: the operating condition, the threat, and the ship itself. The ship observables or detectable signatures, any countermeasures used, performance capabilities and self-protection armament are important factors associated with the ship itself. Vulnerability refers to the inability of the ship to withstand damage mechanisms from one or more hits, to its incivility, and to its liability to serious damage or loss when hit by threat weapons. Ship design features, such as ship size, compartmentation, structural detailing, shock hardening, separation and redundancy of vital components, will affect vulnerability. Recoverability refers to the ability of a ship and its crew to prevent loss and restore mission essential functions given a hit by one or more threat weapons. Recovery capability is a function of the damage control features built into the ship, shipboard allowance of damage control equipment (quantity and type), and crew training and abilities."

Sajdak and Karni (2006) – "Survivability is the time dependant probabilistic indication of a system's ability to obtain or maintain some quantifiably designated capability or performance, subject to a threat type standard as evaluated in a man made hostile environment. Survivability is often broken down into three subcategories… Susceptibility is the time dependant probabilistic measure of the inability of some quantifiably designated capability or performance of the platform to avoid and/or defeat an attack of a threat type standard as evaluated in a man made hostile environment. Vulnerability is the time dependant probabilistic measure of the inability of the platform to maintain some quantifiably designated capability or performance subject to the immediate effects of a threat type standard as evaluated in a man made hostile environment. Recoverability is the time dependant probabilistic measure of the ability of the platform after immediate effects of a threat type standard to obtain some quantifiably designated capability or performance as evaluated in a man made hostile environment."

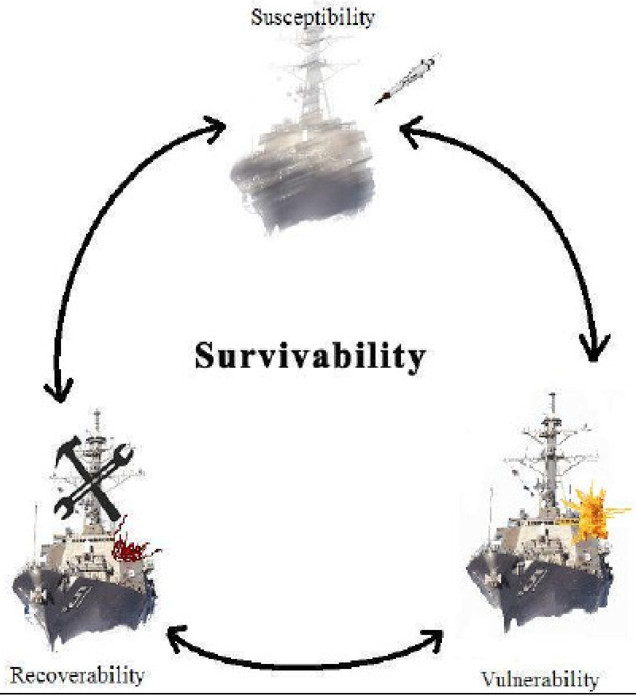


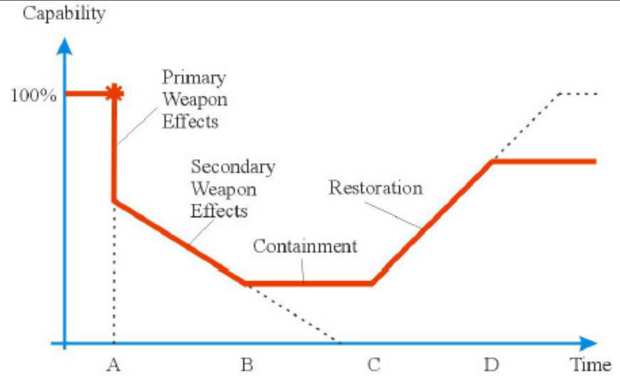
Figure A8: The Three Components of Survivability (Sajdak and Karni 2006)

Schofield et al (2012) – "Survivability is defined as the ability of a platform to complete a mission successfully in a hostile environment. In the naval domain it is broken down into three main areas:

- Susceptibility refers to the probability that the platform is hit, or more generally experiences a damaging event, for instance a missile strike, mine detonation or even an accidental event like a collision;
- Vulnerability represents the probability that the platform loses some form of fighting capability given that the hit occurs; and
- Recoverability measures the chance that the actions of the crew and automated system can control secondary damage and regain lost capability through reconfiguration and repair."

Thornton et al (2006) – "Susceptibility is the probability of being hit… vulnerability is the probability of being damaged, given that the ship has been hit… recoverability is a measure of the time taken to recover from damage and /or the extent to which it is possible to restore the capability."

Turner et al (2006) – "The ability of a warship to complete its mission after an attack depends on its susceptibility (ability to avoid being hit), vulnerability (level of damage when hit) and recoverability (ability to recover from a given damage level) survivability is a combination of these three elements."

	Before point A, susceptibility (signatures, hard/soft kill, sophistication of attack); at point A, primary weapon effects (blast fragmentation, etc.); from point A to point B, secondary effects (fire, flood, etc.); from point A to point B, vulnerability (ship's in built resistance to weapon effects); from point B to point D, containment and restoration; recoverability starts between A and B when DCFF starts (Turner et al 2006).
Figure A9: Capability Versus Time (Turner et al 2006)	

Appendix 4: Survivability Constituents

A4.1 Susceptibility Features

The importance of susceptibility is emphasized by the fact that being able to avoid a hit is better than being able to withstand one (Begg et al 1990; Robb et al 2010), especially when considering modern combatants with a lack of armour (Carter 1988). There are a variety of methods which lead to a reduction in susceptibility; in fact, historically the largest problem has been to locate the adversary (Barnett 1998). Avoiding danger is not a realistic solution for warships (Turner et al 2006); therefore, Belcher (2008) identified four necessary steps in order to avoid a hit:

- Avoid being detected.
- If detected avoid being identified.
- If identified avoid being targeted.
- If targeted avoid being hit.

The above may be achieved by increased situational awareness, managing ship signatures (passive), and having a strong self-defence capability including hard-kill and soft-kill capability (active) (Begg et al 1990; Robb et al 2010). Of these three means of susceptibility reduction, the last two are relevant in the design process and are discussed below. It should be noted that a balance must be achieved between signature reduction and self-defence-capability; the major objective of signature management is to allow effective operation of soft-kill measures, therefore it is unwise to rely only on one the two aspects (Brown 1990; Robb et al 2010).

Stealth can be defined as functions reducing and/or avoiding detection (Friedman 1991; Harney 2010). However, stealth is expensive and difficult to maintain (Harney 2010). Therefore, the general objective is to reduce detectability to a defined acceptable level rather than make the ship invisible (Brown and Tupper 1989; Harney 2010). This can be achieved through signature reduction measures which would make decoys more effective (Foxwell 1990a; Friedman 1991) and by decrease the probability of being detected and classified (Scrase 1991; Papanikolaou and Boulougouris 1998) thus gaining time (Scrase 1991). In addition, signature management is important as it influences the hit location for many weapon types, depending on their guidance system (Andrews and Brown 1982; Papanikolaou and Boulougouris 1998). For example, radar guided missiles target the centre of the radar image, IR guided missiles target hot spots, etc. (Ling 1985). Although a lot of progress has been made in the stealth field over the last years further improvements are limited by advancements in detection and targeting systems of seekers and also by the fact that for certain types of warfare, such as asymmetric warfare, stealth plays a restricted role (Harney 2010). There are a large number of signatures to be managed in a warship and a balance between reduction measures applied across different signatures must be accomplished (Scrase 1991, Harney 2010).

One of the most prominent signatures of a ship is its RCS. Radio waves emitted by radars are then reflected by targets and their RCS is a measure of the reflected power in a given direction, expressed in m^2 or logarithmically in dBms (Foxwell 1990a; Martin 2007). A number of techniques which reduce the RCS of a ship have been identified. Reducing microgeometry is one of them (Foxwell 1990a; Martin 2007), and can be achieved by housing equipment below decks (e.g.: VLS, enclosed masts (Thales 2012)) and behind bulwarks (Friedman 1991; Martin 2007). Such practice would also simplify "maintenance and washing down of nuclear fall-out" (Purvis 1974). Another technique is shaping the hull (flare; which could lead to increased topweight impacting intact stability but improving damage stability (Friedman 1991)) and superstructure (tumblehome; at an angle of at least 7^o (Scrase 1991)) of the ship in order to reflect the radio waves away from the receiver (Dicker 1986; Martin 2007). However, this may impact the structural construction and cost of a ship (Foxwell 1990a; Crow 2001). Certain equipment types can also be shaped (Scrase 1991). Dihedral and trihedral corners (the most efficient reflectors) should be eliminated (Foxwell 1990a; Martin 2007) and flat plates, cylinders and spheres should be avoided (Crow 2001; Martin 2007). RAM which absorbs microwaves at a range of frequencies can be used, especially with equipment difficult to shape (e.g.: doors) (Friedman 1991; Martin 2007) as well as non-electrically conductive material, such as wood and rubber (Martin 2007). In fact Foxwell (1990a) demonstrated that RAM can reduce the RCS of a warship by as much as 75%; however, it requires careful maintenance in order to function efficiently and its performance varies with frequency (Scrase 1991; Martin 2007). A smaller superstructure also results in a smaller RCS (Brown 1987; Begg et al 1990). In addition, the RCS of a ship is a function of its size, implying that smaller ships would return a smaller radar signature (Foxwell 1990a; Harney 2010). Instead of reducing RCS, another approach is to manage it, so that peak returns are concentrated in pre-determined directions (Foxwell 1990a; Friedman 1991) in order to attract missiles to relatively unimportant areas of the ship (Friedman 1991); such a technique was said to be implemented in the Type 23 Frigate (Crow 2001). Moreover, less important ships in a task force can be designed with a higher RCS than the more essential ones in order to draw attack (Friedman 1991). It is important that RCS reduction techniques are applied in a consistent manner in order to achieve maximum effectiveness; Figure A10 shows the effect of not combining sloped sides with reduced microgeometry.

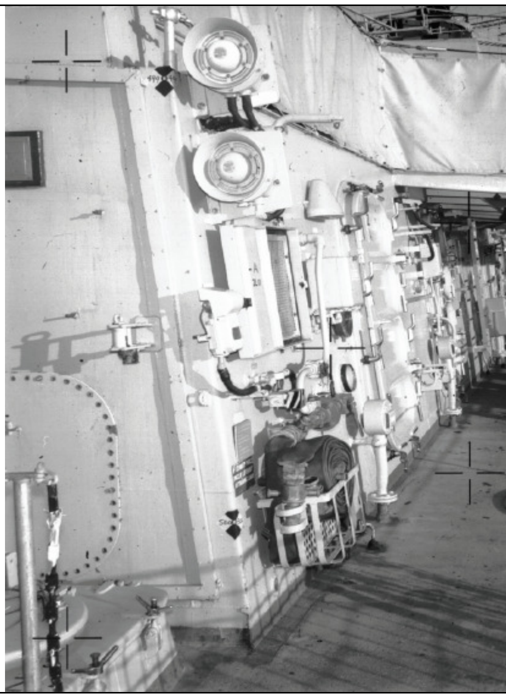


Figure A10: Nice Slopes – Shame About the Microgeometry (Martin 2007)

Despite certain cost concerns, Robb et all (2010) demonstrated that for 5,000te surface combatant, shaping of the hull and superstructure, reducing external microgeometry and applying RAM resulted to an increase of the UPC by less than 0.5%.

The IR signature of a naval ship is another aspect requiring attention. It depends on the ship's surface temperature which is influenced by the radiation incident upon it, its absorbability, reflectivity, thermal conductivity and heat capacity (Foxwell 1990a). A ship which generates heat through its various equipment, usually stands out against the cold sea (Scrase 1991). The IR signature can be used in order to locate and identify targets during harsh weather conditions or at night, using equipment such as IR cameras, image intensifiers, TV and laser rangefinders (Foxwell 1990b). IR imaging can be exploited in order to collect information concerning ship layout and propulsion system (Foxwell 1990a). Also, since IR sensors are passive, heat seeking missiles have a high level of immunity to jamming and give little warning to the target (Foxwell 1990b). Although most of the ship's hull has a surface temperature approximately equal to ambient temperature, there exist certain hot spots (Foxwell 1990a). The designer's aims are to identify and reduce the temperature of hot spots, as well as to produce a uniform signature (Foxwell 1990a). Hot spots include exhaust gasses, exhaust uptakes and areas in their vicinity, machinery spaces, sun warmed plating (Foxwell 1990b; Belcher 2008). Techniques for controlling the IR signature include cooling the exhaust by mixing it with cooler ambient air (Foxwell 1990a; Belcher 2008), applying IR suppressors around uptakes (Friedman 1991; Afanasieff and Mabry 1994) cooling and insulating surfaces (Foxwell 1990a; Belcher 2008), hiding or masking hot metal parts (e.g.: enclosing exhaust uptakes within structure) (Belcher 2008), applying low emissivity coatings to structural hot spots (Foxwell 1991a; Scrase 1991), etc. Furthermore, engines could exhaust underwater, therefore eliminating the exhaust plume signature (Heather 1990; Foxwell 1990a), however this is likely to have an impact on the underwater acoustic signature and raise back pressure and corrosion related issues (Dicker 1986; Belcher 2008). The IR signature would also decrease if the engines exhausted just above the waterline (Dicker 1986; Afanasieff and Mabry 1994). Robb et al (2010) demonstrated that for 5,000te surface combatant, managing the exhaust plume and solar reflection IR signatures resulted to an increase of the UPC by less than 0.5%.

The treatment of a ship's visual signature lost its significance after the advent of naval radars during WWII (Friedman 1991). However, its prominence has been partly regained due to the development of stealth technology (that allows ships to move closer to the adversary before being identified), the increase in littoral operations (occurring close to the coast and in congested waters) and the developments in electro-optic sensor technology (Friedman 1991). The general techniques for reducing the visual signature of a ship are to choose an appropriate paint scheme in order to blend in, avoid contrast with ship outline (e.g.: do not paint funnel tops black to hide exhaust stains), reduce ship size, avoid identifying features (such as unique radomes), etc. (Friedman 1991). However, certain aspects, such as a ship's wake, which extends for numerous miles, cannot be eliminated (Friedman 1991).

When considering subsurface warfare, the acoustic signatures produced by ships allow detection and classification, mine activation and torpedo targeting (Brown and Andrews 1980; Foxwell 1991a). Such signatures can travel for long distances since water is an excellent noise conductor and can be used to identify a ship class or even a particular ship and its speed (Foxwell 1991a; Belcher 2008). Further reasons for treating such signatures include the degradation of the performance of the ship's own sonar (Gallin and Lemenkuhler 1989; Foxwell 1991a) and the worsening of the crew's working and living conditions through airborne noises (Gallin and Lemenkuhler 1989). Fluid borne and airborne noise sources include flow turbulence (Andrews and Brown 1982; Belcher 2008), rotating components (Foxwell 1990a), fluid borne noise along piping to seawater outlets (Belcher 2008), etc. However, the propulsion plant (engines, gears, propellers, etc.) is the main source (Gallin and Lemenkuhler 1989; Foxwell 1990a) and therefore, extensive research has been carried out in the power transmission noise reduction area (Gallin and Lemenkuhler 1989). At low speeds machinery noise reduction is the priority, while at higher speed propeller cavitation reduction (Brown and Andrews 1980; Foxwell 1990a). Figure A11 summarises the main propulsion plant noise sources on a ship.

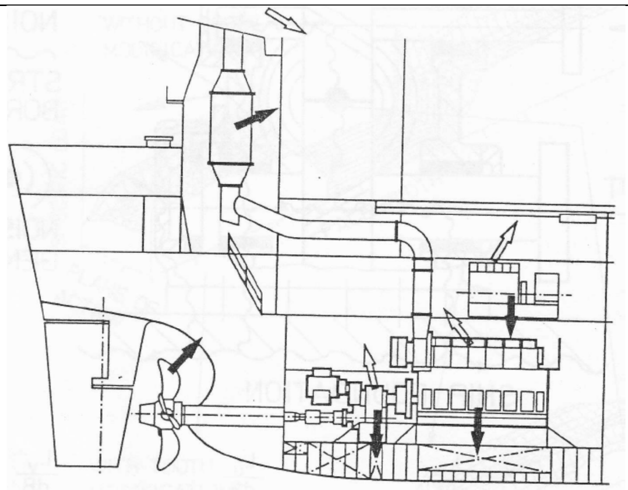


Figure A11: Main (propulsion plant) Noise Sources on a Ship (Gallin and Lemenkuhler 1989)

The acoustic signature of naval ships can be treated by reducing noise sources (e.g.: using low vibration properly maintained equipment, travelling at speeds below propeller cavitation, etc.) (Belcher 2008), using anechoic tiles and coatings (extensively used on submarines, but for limited range of frequencies and regularly need replacement) (Foxwell 1991a; Belcher 2008), employing vibration isolators and resilient mounts which can also protect from shock of underwater explosions (Gallin and Lemenkuhler 1989; Robb et al 2010), using insulation enclosures and housings (Gallin and Lemenkuhler 1989; Belcher 2008), covering the underwater part of the hull with film of small bubbles (Brown and Andrews 1980; Belcher

2008), avoiding underwater exhausts (Heather 1990), regularly monitoring acoustic signatures (Belcher 2008; Scrase 1991), etc. In addition, the choice of propulsion system is vital in the acoustic signatures field (Foxwell 1991a; Scrase 1991). Developments of IFEP introduce benefits in noise reduction (Hudson et al 1996; Gates 2005), mainly due to the absence of a gearbox (Gallin and Lemenkuhler 1989; Gates 2005). Also, engines can be mounted higher up in the ship therefore elongating the noise path to the water (Scrase 1991; Gates 2005). Moss (1990) researched the acoustic performance of SWATHs and concluded that their improved performance is due to the ability to install most major noisy equipment in the box structure, above the waterline, presenting a good solution for an ASW ship, where noise reductions is a main concern (Foxwell 1990a). A noise reduction flow diagram for a surface ship from (Foxwell 1991a) is reproduced below.

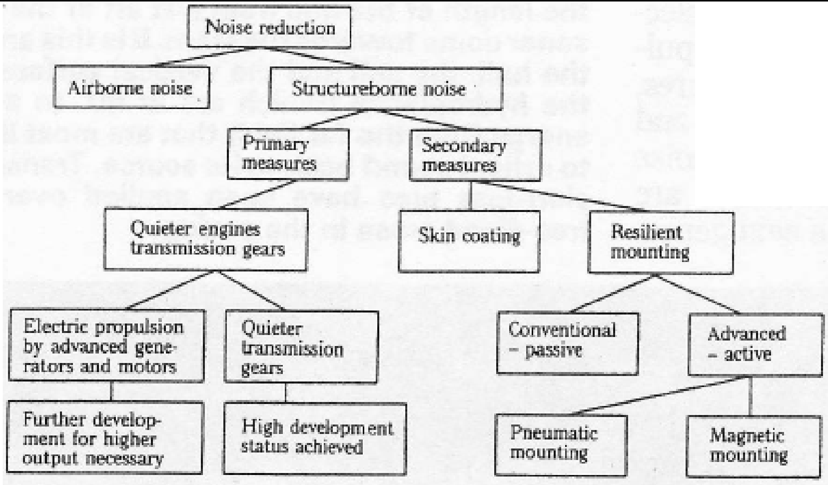


Figure A12: A Noise Reduction Flow Diagram for a Surface Ship With Primary and Secondary Measures for Structurebourne Noise (Foxwell 1991a)

Many of the above solutions have an impact on weight and space and should therefore be considered early in the design (Heather 1990; Foxwell 1990a). Rob et al (2010) looked at the cost implications of acoustic signatures treatment for a 5,000te frigate and concluded that improvements in propulsion, power, key auxiliary systems, and acoustic quieting techniques (which share common features with shock protection) accounted for a 2.1-2.8% increase of the UPC.

A further underwater signature is the magnetic field (with both permanent features and those varying with heading and location, described in detail in (Ross et al 2012)) produced by a steel ship and its electric machinery (Belcher 2008; Ross et al 2012). This can be treated through passive measures such as constructing the ship of non-magnetic material (which is the case with some mine-hunters), and active measures such as using a degaussing system (powered coils which produce an equal and opposite magnetic field to cancel the magnetic signature) as well as through the monitoring of the magnetic signature (Belcher 2008; Ross et al 2012). Furthermore, the reaction between the dissimilar metals of the hull (steel), propeller/shafts (brass/bronze) and cathodic protection (zinc) in seawater (an electrolytic solution) produces a low frequency electromagnetic wave signature (Foxwell 1991a; Ross et al 2012). This can be managed through the use of sacrificial anodes, the use of non-conducting material for propellers and shafts, the proper maintenance of hull paint, the use of a shaft grounding system, the monitoring of the electric signature, etc. (Foxwell 1991a; Belcher 2008). Robb et al (2010) concluded that for a 5,000te frigate, employing a degaussing and impressed current control system against mine and torpedo detection would be of minimal cost.

However, even if all the above signatures are effectively treated, a warship's position is likely to be revealed by its electronic emissions through passive electronic warfare known as ESM (Kiely 1988; Bouloujouris and Papanikolaou 2004). Pakenham (1989) defines ESM as "techniques to exploit enemy's use of electronics (rather than degrade them) to support one's own tactic" and, as shown in Figure A13, can be considered part of Electronic Warfare.

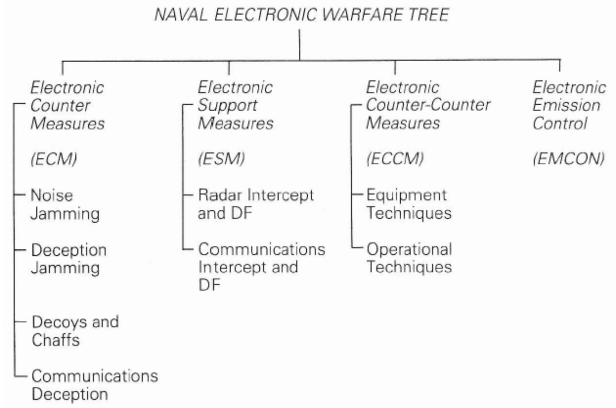
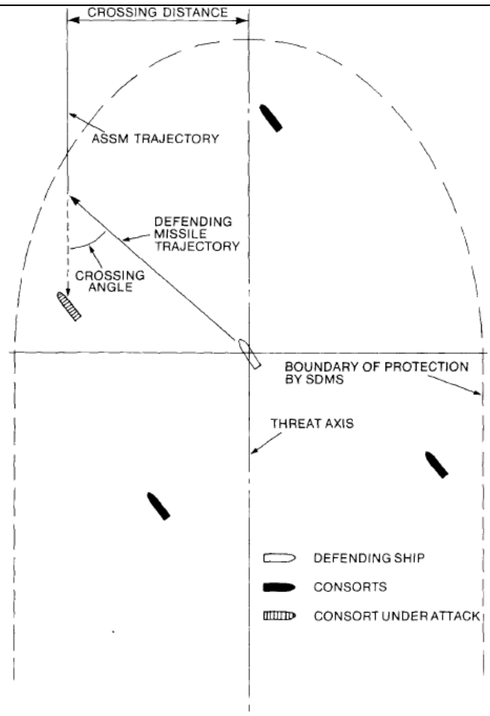


Figure A13: Naval Electronic Warfare Tree (Pakenham 1989)

Kiely (1988) describes various equipment which could be used for ESM. EMCON, sometimes considered part of ECCM, can counter ESM techniques (Pakenham 1989). For example, standardising equipment (e.g.: radars) complicates the identification of the emitter (Friedman 1991), the use of GPS for navigation (rather than navigation radars) reduces emissions (Lok 1993); further techniques are given in (Kiely 1988).

Besides signatures (and situational awareness), the remaining essential component of susceptibility is a ship's self-defence capability. This is also known as active defence and has the objective to destroy, degrade or deceive the threat targeting the ship (Harney 2010). Traditionally, ships relied on layered defence systems including soft-kill and hard-kill components, in order to defend against saturation attacks (Brown 1986b; Harney 2010). Hard-kill systems aim to destroy incoming weapons in flight (Brown 1990). They include long and medium range ship launched defensive missiles for outer defence and PDMS and CIWS for inner defence (Afanasieff and Mabry 1994; Harney 2010), with a high degree of automation and adjustable (missile) flight, due to the timescales involved and for improved effectiveness (Longworth 1983)). However, certain threats such as ASMs are becoming increasingly difficult to counter, not only due to their increased speeds and evasive manoeuvrability, but also due to the requirement to respond to crossing targets, as shown in Figure A14.



ASSM: Anti Surface Ship Missile

Figure A14: Coverage Provided By Supporting Defence Missile System (SDMS) (Adams 1988)

The performance of defensive missile systems against incoming missiles is highly dependent on the angle between the defensive and attacking missiles (Adams 1988). This is clearly shown in Figure A15 and Figure A16, which were provided by Dstl and illustrate unclassified relative probabilities of kill (with 0.6 being the maximum achievable) of various defensive missile systems for various crossing target angles.

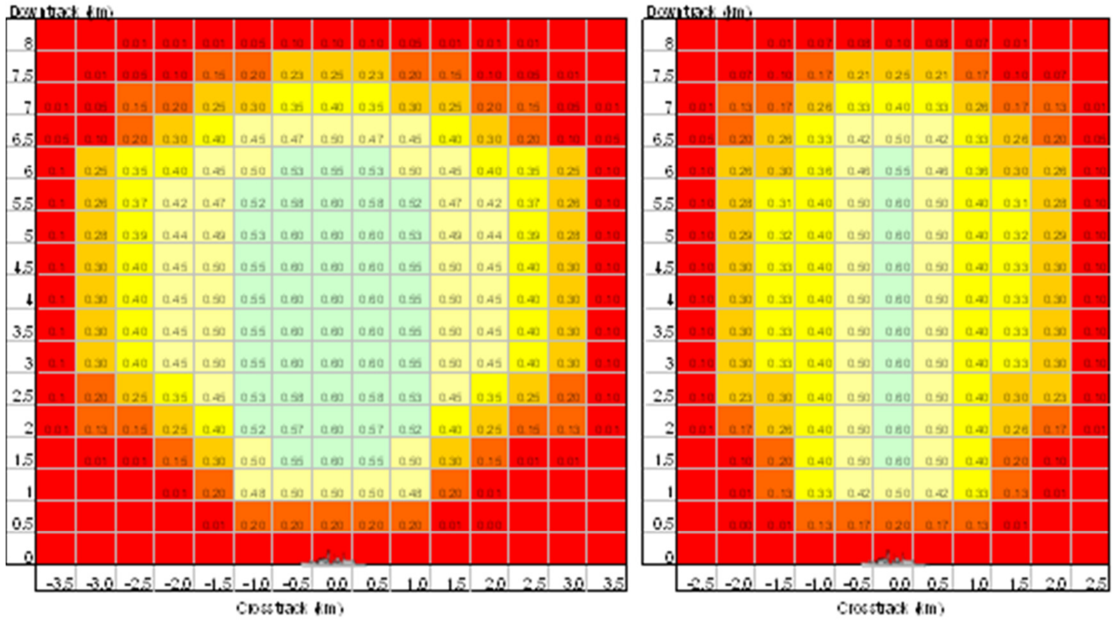


Figure A15: Point Defence Missile – Performance Against Subsonic Missile (left) and Supersonic Missile (right)

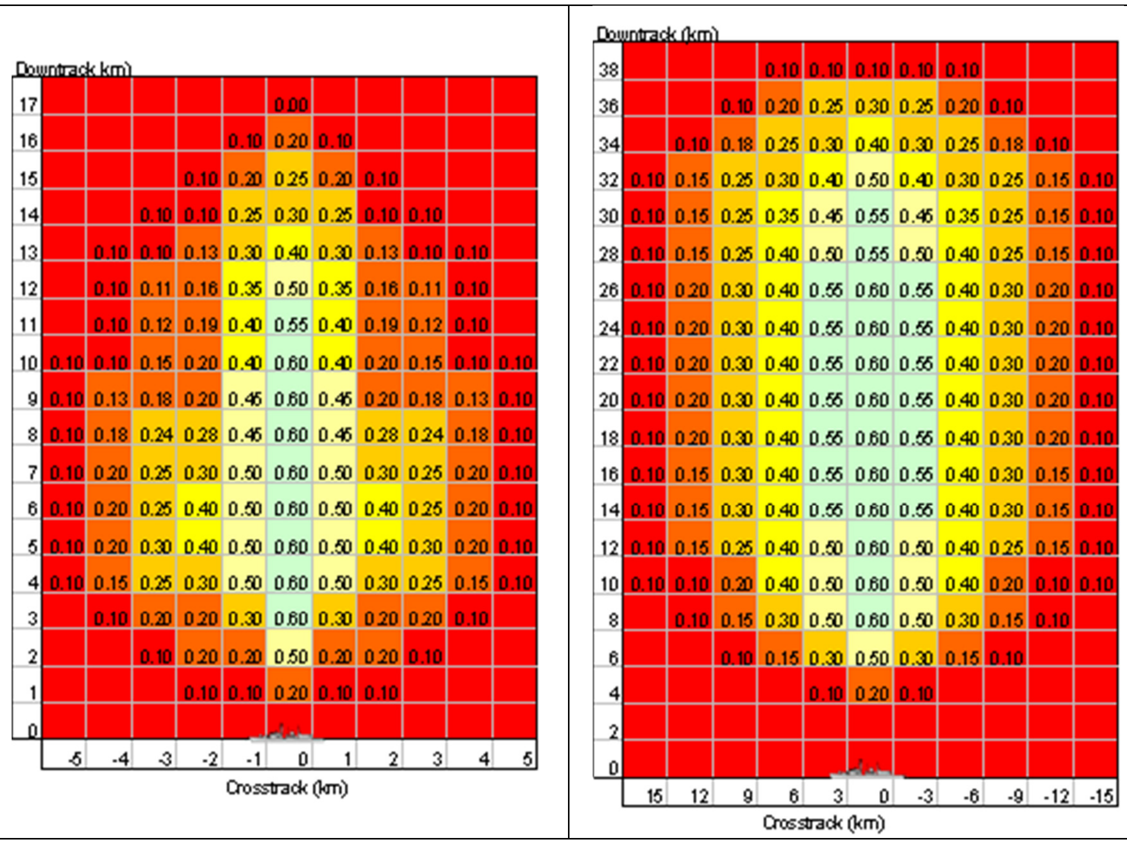


Figure A16: Medium Range Missile (Left) and Long Range Missile Performance Data

Soft-kill is also known as ECM (Figure A13) and is defined as “techniques and equipment to counter/spoil the enemy’s use of electronics” (Pakenham 1989). ECM includes jamming of radar, IR and communications, electronic false targets and missile break-lock devices and decoys, such as chaff and IR flares, which can be used to distract by presenting alternative targets to a missile radar during its search phase, or seduce by breaking the lock of a missile that has already located the target ship (Kiely 1988; Afanasieff and Mabry 1994). Acoustic decoys are also used for protection against torpedoes (Brown 1990; Foxwell 1991b). A detailed description of jammer and decoy/decoy system types can be found in (Kiely 1988), where ECCM techniques are also said include anti-jamming and anti-decoy measures.

It is worth noting that high speed and manoeuvrability, which may be achieved through decreasing ship size, reduces a ship's susceptibility (Harney 2010). In fact, many authors agree that a fleet comprising of many relatively small and cheap ships of modest capability would be more effective than a small fleet of high capability ships, (Brown 1986b; Harney 2010). However, that would incur extra cost but provide a greater naval presence (Harney 2010).

In conclusion, the susceptibility of a warship heavily relies on decisions taken by requirement setters, designers and operators (Ball and Calvano 1994). Various signature types should be considered, as well as EW, defensive and offensive weapon systems, manoeuvrability and tactics (Ball and Calvano 1994).

A4.2 Vulnerability Features

During the Cold War, vulnerability of ships was of secondary priority, as it was assumed that due to the development of nuclear weapons, it was only worth emphasizing attack capabilities (Ball and Calvano 1994). Due to the change to a wider range of threats over the last two decades, the ability to survive and recover from a hit has evolved into an important aspect of ship design (Ball and Calvano 1994). The complexity and diversity of modern threats implies that even with the advancements made in stealth and self-defence technology, there is still a likelihood of a ship being hit and so it must withstand a range of weapon effects (Heywood and Lear 2006; Harney 2010). Examples of susceptibility systems failing to provide the necessary protection range from WWII (Brown and Brown 1986) to the Falklands and Gulf conflicts (Martin 1998; MOD 2001). For example, in 1987, the USS Stark, with a modern layered defence system was hit by 2 Exocets fired by an Iraqi fighter (Martin 1998). Harney (2010) estimated that an EW system would be effective against about half of the missiles which evaded the hard-kill defences. Moreover, even weapons which are effectively countered by ship's defensive systems might result in near misses, causing fragment and shock damage (Andrews and Brown 1982; Dicker 1986). In addition, a ship merely relying on its defensive systems can still be vulnerable to collision, fire, susceptibility systems deficiencies (Brown 1990). Another issue that increases the importance of design for vulnerability in naval ship design, especially at the early stages, is that it cannot be addressed after the ship has been constructed (contrary to some susceptibility issues such as RAM, IR suppression devices, special paints and coatings) (Boulougouris and Papanikolaou 2004). As with susceptibility, vulnerability reduction measures are a multi-stage process, defined by Belcher (2008) as:

- If hit, avoid being damaged.
- If damaged, continue fighting.
- If unable to continue fighting, allow ability to withdraw.
- If crippled allow time to evacuate.

Correspondingly, Ball and Calvano (1994) gave four different ship kill definitions:

- Total Kill: Ship is lost entirely because sinking occurs or fire (or other phenomenon) forces abandonment
- Mobility Kill: immobilization or loss of controllability occurs.
- Mission Area Kill: Particular ship mission area (e.g. AAW) is lost.
- System Kill: Damage to one or more components results in loss of a system.

Before considering the various vulnerability reduction techniques, one must have a clear understanding of the weapon types and effects a ship might encounter, and more specifically, the primary weapon effects; i.e.: the effects which occur instantly with the weapon detonation (Herman and Loeser 1992; Reese et al 1998). Brown (1990) grouped weapon effects under the categories of fire, flood, structural collapse, shock, blast and impact, the last four being primary effects. Figure A17 illustrates the available conventional weapons.

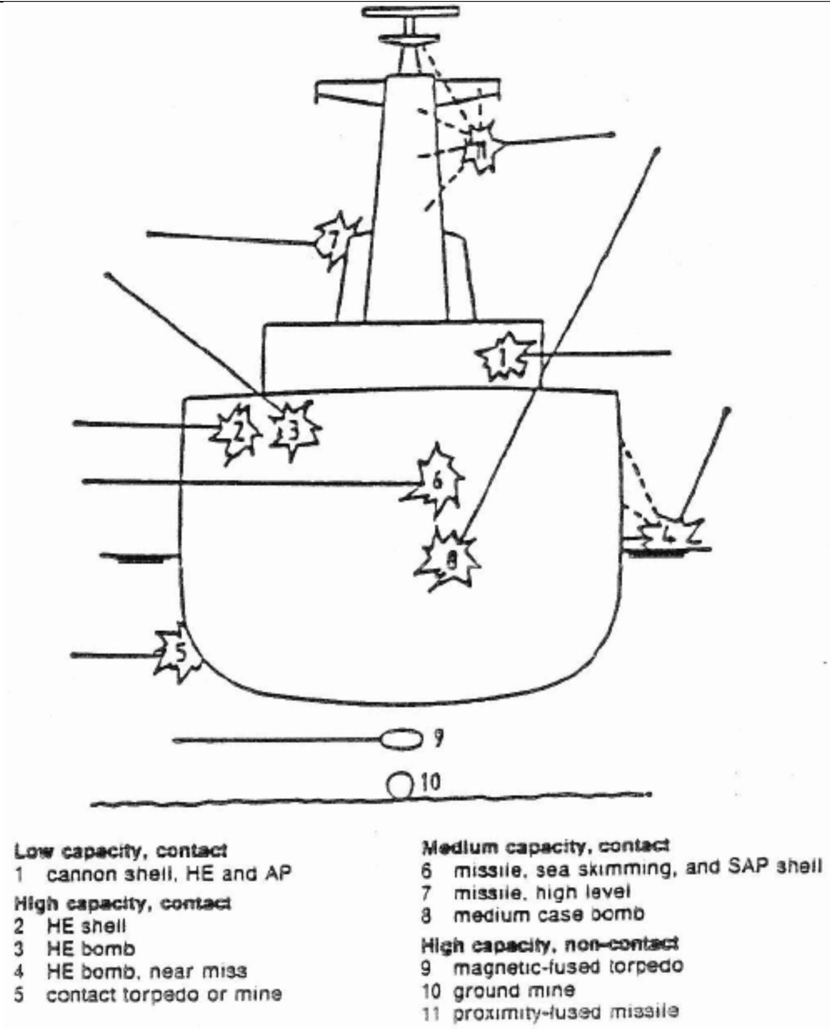


Figure A17: Available Conventional Weapons (Brown 1990)

Said (1995), on the other hand, suggests the following weapon based categories:

- Air-delivered weapon, conventional warhead.
- Air-delivered weapon, nuclear warhead.
- Air-delivered weapon, CBR warhead.
- Underwater-delivered weapon, conventional warhead.
- Underwater-delivered weapon, nuclear warhead.

The foremost anti-ship weapon is the ASM (Longworth 1983; Surko 1994) and is often fused in order to explode before/on contact or after penetration (Chalmers 1993b); however the most lethal effects are caused by underwater weapons (Preston 1990). This was proven in WWII, where the most frequent cause of ship loss was due to loss of watertight integrity from torpedo hits (and less frequently by mines and aerial bombs) (Korotkin 1960; Brown and Brown 1986; Brown 1997). Examples of modern ships being hit are HMS Sheffield and USS Stark sustaining ASM hits; and USS Samuel B. Roberts, USS Tripoli and USS Princeton being damaged by mines (Said 1995). The following paragraphs will look at primary weapon effects in more detail.

The initial effects of an abovewater projectile are due to the kinetic energy transmitted into the structure (Martin 1998; Pugh 2006). The magnitude of damage depends on weapon speed and mass and damage is in the form of holes punched, broken pipes and cables (Belcher 2008), with poorly protected, non-redundant equipment being most vulnerable (Turner et al 2006). If the weapon includes depleted Uranium (or if it hits volatile material) it may ignite therefore causing further heat damage (Belcher 2008).

Another form of damage is through fragmentation, where the explosion inside the weapon casing breaks it into energised fragments which penetrate through the ship (Pugh 2006; Belcher 2008). Shells, with relatively small warheads, cause most of their damage through splinters (Brown 1990; Chalmers 1993b), as do abovewater bombs exploding close to the ship (Brown and Brown 1986; Brown 1997) and externally exploding ASMs (Brown 1986b; Martin 1998). Weapon casings are sometimes preformed to produce fragment patterns and their velocity depends on the ratio of charge weight to casing weight (Chalmers 1993b). Fragments can weaken structure by penetrating bulkheads, and also damage cables, pipes, personnel, aircraft, electronics (Turner et al 2006; Belcher 2008), and vulnerably located unarmoured sensors (Carter 1988; Belcher 2008). The effects of fragmentation damage are shown in Figure A18.

Figure A18: Fragmentation Damage (Turner et al 2006)

A shaped charge may be used in order to penetrate almost any material, including thick armour (Belcher 2008). It works by generating a jet of molten metal at high velocities which burns its way inside the ship (Belcher 2008). Damage is caused by spraying the ship's interior with molten metal which may penetrate bulkheads or even magazines which leads to devastating consequences (Belcher 2008). Since the effects are more severe if a weapon explodes internally (Belcher 2008), a shaped charge may be used to penetrate inside the ship (Chalmers 1993b). Alternatively, an armoured piercing warhead could be used (Belcher 2008).

The most common effect of abovewater weapons is blast; this is the dominant effect of internal ASM explosions (Brown 1986b; Martin 1998). A chemical explosion generates heat and a rapid expansion of air, therefore building up an expanding high pressure wave which progresses along the least resistance path, such as passageways (Begg et al 1990; Belcher 2008). Structure and equipment close to the detonation point are destroyed due to the extreme heat (which could cause ignition, melting or vaporisation), whereas damage to equipment, services, personnel and structure (e.g.: buckling of watertight doors, rupturing of steel structures in confined spaces) at a distance is caused by the pressure wave and propelled debris (Begg et al 1990; Belcher 2008). The effects of blast are clear in Figure A19.

Figure A19: Blast Damage (Turner et al 2006)

Eventually, equilibrium will be re-established when the explosion is vented to the atmosphere (Tozer 1993; Belcher 2008). Chalmers (1993b) presents methods to carry out rough estimations of blast loadings.

The underwater equivalent of blast is underwater shock; however it is more lethal due to the incompressibility of water (Belcher 2008). Underwater weapons include torpedoes, mines and near miss bombs or shells exploding underwater (Brown and Brown 1986; Bradbeer and Andrews 2012b). The initial effect of an underwater explosion is shock waves transferred through the water into the structure causing high acceleration, small displacement motions; whipping may also occur by the expanding gasses creating a bubble which collapses and re-expands in cycles, causing resonant oscillation (Begg et al 1990; Pugh 2006). If the explosion occurs close to the hull, shock waves will cause localised effects, with equipment machinery and personnel being damaged, and possible flooding occurring by rupturing of local structure (Chalmers 1993b; Belcher 2008). More distant explosions cause shock effects to the entire hull (Belcher 2008) and violent whipping could buckle the decks or even break the ship's keel (Brown 1990; Turner et al 2006) as was observed during WWII (Brown and Brown 1986).

Finally, the effects of nuclear, biological and chemical weapons must be considered. Nuclear weapons are characterised by their massive magnitude of destruction (Belcher 2008). Their effects on ships are highly dependent in the distance to the detonation location (Begg et al 1990; Belcher 2008). Nuclear weapons can explode both above and underwater and can be treated as conventional explosions (Begg et al 1990) with the additional effects created by an EMP which damages electronic equipment, a thermal pulse which vaporises, weakens and ignites material and radiation fluxes (Chalmers 1993b; Belcher 2008). Conversely, chemical and biological weapons (with the addition of radiation mentioned above) are aimed towards the crew and cause little damage to structures (Belcher 2008).

After consideration of the main primary weapon effects a ship might encounter, it is now possible to look at different vulnerability reduction strategies. Martin (1998) suggests that the initial response to the hit depends on system layout, structural strength and degree of protection. Begg et al (1990) identifies two vulnerability reduction categories; protection (built in measures reducing initial damage such as structural integrity, zoning and increased stability margins) and counter action (which is more relevant in recoverability). Increased emphasis is placed on the concept of concentration, duplication and separation and protection (Brown 1990; Martin 1998). Heywood and Lear (2006) state that the key to vulnerability reduction is careful watertight subdivision, machinery layout, magazine and fuel and stores locations. Schofield (2006) lists a six step strategy for vulnerability reduction developed by the MOD and QinetiQ:

- Prevent catastrophic loss.
- Reduce critical elements.
- Concentrate critical elements.
- Separate redundant elements
- Hardening.
- Hit point management.

From past experiences it was also observed that naval ship vulnerability increased by employing ships for tasks they were not designed for (Brown 1997). As can be seen, there are many vulnerability reduction techniques with many similarities, which are discussed in detail in the following paragraphs. However most authors agree that vulnerability reduction features must be designed at the early stage in order to gain both cost and effectiveness benefits (Tozer 1993; Martin 2007). Furthermore, Surko (1994) recommends that design criteria aiming to minimise damage should exist.

The most important method of managing ship vulnerability is through the careful development of the layout (Brown 1986b). Vulnerability considerations are vital in the layout development of modern warships also due to the lack of armour (Chalmers 1993b). Due to the relatively small warheads on modern ASMs, blast and fragment effects are usually localised (Harney 2010). Critical equipment and compartments are usually located low in the ship to protect from abovewater weapons, although care needs to be taken as they will be subject to greater shock levels, especially if they are mounted on the double bottom or on a main transverse bulkhead (Begg et al 1990; Heywood and Lear 2006). In addition, there is not enough space for all critical items to be placed deep, so priority is given to high risk compartments (command & control spaces, magazines, etc.) (Brown 1987; Belcher 2008) and heavy compartments (machinery, fuel, etc.), also for improved stability (Begg et al 1990; Heather 1990). It is worth noting that many WWII warships suffered extensive damage after explosions of upperdeck torpedo magazines (Brown and Brown 1986). Another philosophy supports the location of the low density command and control spaces above the waterline and closer to masts and aerials in order to minimise the length, and therefore vulnerability, of cables and other connectivity items (Brown 1987; Begg et al 1990) and the decentralisation of such spaces to avoid catastrophic consequences (Brown 1987; Heather 1990). A certain level of protection could be offered to such compartments by placing them inboard, protected by less critical spaces or side passageways (Begg et al 1990; Harney 2010). Additionally, critical spaces are usually located away from high probability of hit areas identified by computer programmes (Brown 1987; Covich 1988). A ship's layout can also be arranged to minimise blast consequences. By avoiding long straight passageways, shaping compartments, selecting appropriate door opening directions and not locating equipment on load paths and corners, a blast resistant structure could be achieved (Chalmers 1993b; Harney 2010). Also, corner structures should be avoided or reinforced (Heather 1990; Belcher 2008). A final step in achieving a blast resistant layout is by including 'blow-off panels' in order to vent the explosion to the atmosphere (Begg et al 1990; Belcher 2008); this is more effectively done through the upperdeck, therefore, favouring a small superstructure (Begg et al 1990). A warship should also be able to remain contamination free against NBC weapons. This is done by dividing either the entire ship or only the most vital spaces into gas tight citadels replenishing air with NBC filters (Purvis 1974; Afanasieff and Mabry 1994). Access to citadels is provided through airlocks and access to the weather through decontamination stations (Begg et al 1990; Afanasieff and Mabry 1994). The concept of zoning, which is discussed later, could provide advantages in keeping the ship uncontaminated (Begg et al 1990). It is argued that unconventional configurations, such as trimarans, provide benefits in vulnerability reduction from layout considerations due to the greater choice in compartment location given by the large amidships box structure and upperdeck (Andrews and Hall 1995; Andrews 2004).

A specific vulnerability reduction strategy related to the ship's layout is adoption of concentration, separation and duplication. This shares similarities to the successful unit system of machinery of some WWII ships (Brown and Brown 1986). It is especially relevant for modern ships since their weapon systems rely on many separated components in contrast to the autonomous WWII guns (Tozer 1993). All components of a system in series should be located in close proximity (e.g.: equipment rooms should be located close to the corresponding weapon/sensor (Covich 1988)) in order to minimise the probability of disabling a system with a single hit (Brown 1991; Belcher 2008). Redundant systems (not only for survivability but also for availability, reliability and maintainability (Cerminara and Kotacka 1990; Martin 2007), e.g.: electrical generation and propulsion units (Heather 1990; Doerry 2007)) must be appropriately separated in order to take full advantage of the concentrated systems (Brown 1991; Randles 2009). The separation distances are usually set by weapon radius of damage (Belcher 2008). Service redundancy and separation can be provided by running pipes and cables along side passageways (Brown 1987; Afanasieff and Mabry 1994). The combat system and the crews living/working quarters could also be separated into a forward and aft configuration to enable 'fighting hurt' (Brown 1987; Afanasieff and Mabry 1994). Figure A20, Figure A21 and Figure A22 illustrate the concept of concentration, separation and duplication.

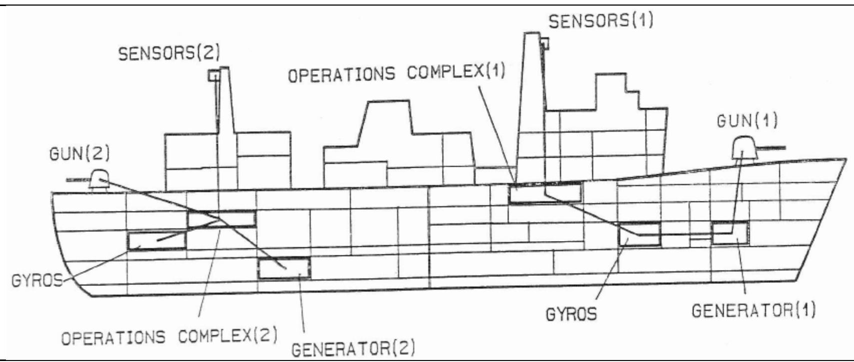


Figure A20: Concentrating and Duplicating Equipment for the Gun System (Tozer 1993)

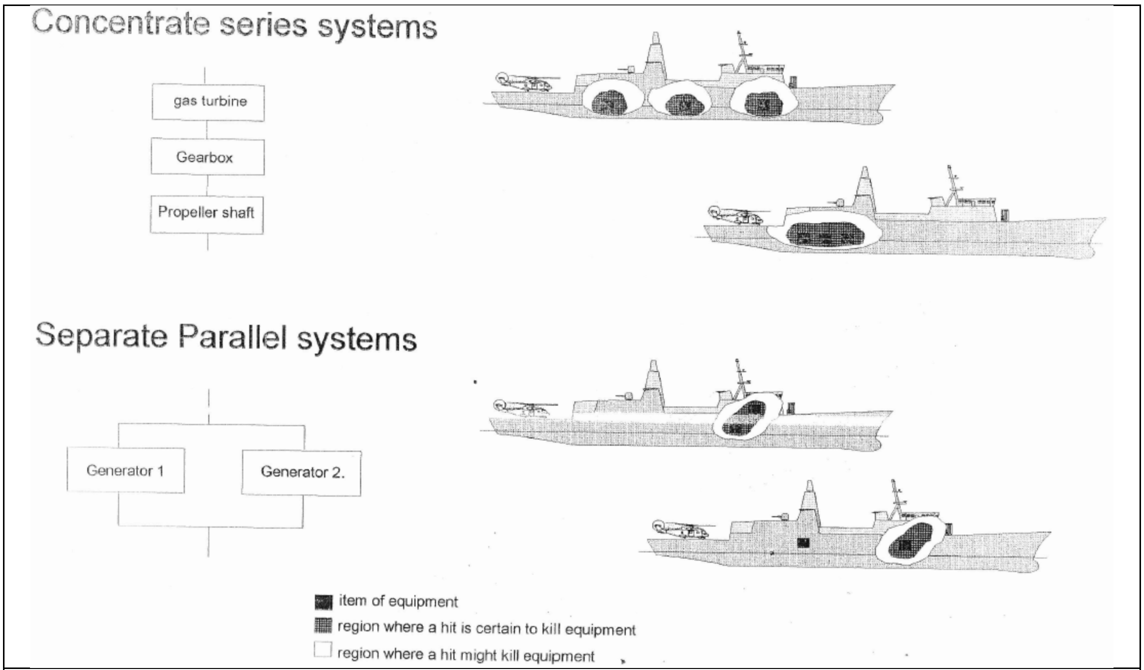


Figure A21: Improving System Survival by Concentrating, Duplicating and Separating (Martin 1998)

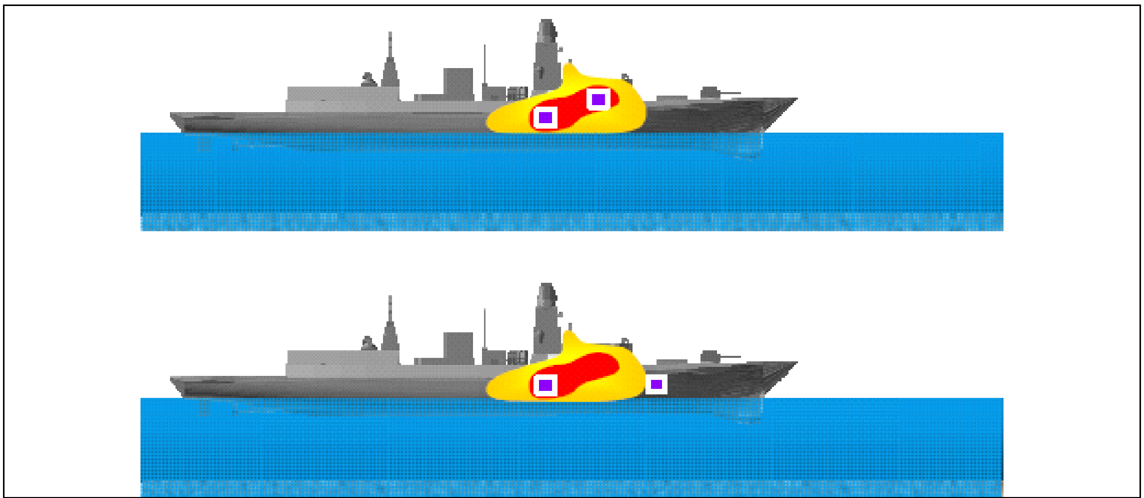


Figure A22: Separate Redundant Components (Turner et al 2006)

However, it is not practical to duplicate and separate every system (Brown 1986b; Tozer 1993) and separation is always constrained by ship size (Reese et al 1998). Providing a secondary Operations Room would be expensive, separating services on port and starboard sides would mean that services would be vulnerable to small arms (and in the case of delay fused missiles exploding amidships, both service lines might be damaged), separating machinery rooms can lead to long shafts, etc. (Brown 1986b). However, costs arising from adopting duplicate systems may be decreased by using commercial equipment (Tozer 1993; Bricknell and Vedlog 2007). In addition, Robb et al (2010) when examining the cost of survivability features on a 5,000te frigate, observed that cost savings could be made by using common consoles and concluded that redundancy and separation of key systems (combined with hardening which is mentioned later) is the most cost effective survivability feature. Also, with the developments of IFEP, widely separated forward and after propulsors could be provided with spread out engines, overcoming the long shaft problem (Hudson et al 1996; Linklater 2012) (although forward propulsor noise could interfere with the ship's own sonar (Doerry 2007), and widely separated funnels are likely to have a large impact on the upperdeck (Brown 1987)). Finally, a centreline passageway could protect services from small arms, and services could be duplicated deep in the hull (as in Figure A23) (Brown 1990).

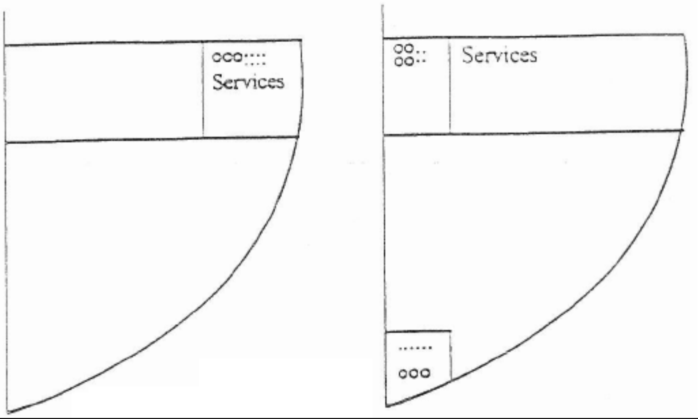


Figure A23: Service Duplication (Brown 1990)

Another important vulnerability reduction measure is increased ruggedness of equipment and systems (Begg et al 1990) especially when concentration, separation and/or duplication are not practical (Tozer 1993; Robb et al 2010). Hardening can be achieved through the use of shock resistant mounts to critical equipment (such as propulsion and auxiliary machinery (Cerminara and Kotacka 1990; Afanasieff and Mabry 1994)) (Begg et al 1990; Belcher 2008) and flexible couplings for pipes and cables (Begg et al 1990). Raising shock standards is likely to be expensive (Tozer 1993) but such costs may be reduced by decreasing the number of equipment being protected (Brown 1986b). Shock mounts of critical equipment should be designed to withstand a shock level approximately equal to lethality level at which structural integrity is lost (Crow 2001) and are usually tested through full scale shock trials on the FOC (Belcher 2008; Brown 1990). Furthermore, protection could be provided by the use of armour (Dicker 1986; Jones and Kimber 2012) to systems (cables, pipes, high pressure air, weapons, sensors, etc.) and critical compartments (Brown 1986b; Petersen 2006). Armour, (in the form of steel or modern lightweight but expensive composites) is attractive for littoral and asymmetric warfare (Chalmers 1993b; Harney 2010) and can reduce the damage caused by fragmentation (and blast to a limited extent) (Brown 1986b; Harney 2010). For a typical frigate, approximately 50te of armour (Dicker 1986; Begg et al 1990) and 20te of additional fire protection to essential services and compartments would provide with large benefits (Begg et al 1990). Protection to equipment, systems and compartments could also be provided through blast resistant structure (such as blast resistant bulkheads and doors) which would reduce the longitudinal extent of damage (Martin 1998; Robb et al 2010); this is clearly demonstrated in Figure A24.

	Normal watertight doors can become projectiles under blast loading.
	Blast hardened doors may survive up to full failure pressure of a bulkhead.

Figure A24: Normal vs. Blast Hardened Watertight Doors (Martin 2007)

Increased effectiveness would be achieved if combined with a blast resistant layout and concentration, duplication and separation (Belcher 2008; Robb et al 2010). Robb et al (2010) who studied the cost effects of survivability features in a 5,000te frigate remarked that the cost increase of different hardening techniques is relatively small compared to the UPC, although the use of armour could have an impact on weight (and therefore cost), depending on the protected area. Begg et al (1990) estimated that approximately 40te would be added to a 7 zone frigate by increasing zone bulkhead thickness to 12mm for improved protection. In addition, further advantages are presented if hardening is combined with redundancy and separation; also shock protection devices can be beneficial in reducing the acoustic signature of ships (Robb et al 2010). However, if such features are added to the ship after construction, costs would increase significantly (Martin 2007). Another area which has to be addressed is extending the use of commercial equipment to save cost (Martin 1998). Such equipment is not designed against blast and shock; therefore, the cost savings could be invested in hardening and duplication (Martin 1998).

A specific system which requires hardening in naval ships is the structure itself (Covich 1988). In structural design, the main input is the wave loading (Brown and Tupper 1989) but the structure must resist and contain damage (Chalmers 1993b). Once the structural integrity is compromised, the ship will not be able to carry on its mission (Belcher 2008); in fact, naval ship sinking is usually a result of structural collapse (Brown 1986b). Moreover, damaged structure inhibits access and assists the spread of secondary damage (Manley 2012). Therefore sufficient residual strength should be provided (Belcher 2008), but care should be taken when designing the structure as blast effects are attenuated with hardened structure (Brown 1990). An effective structure can be achieved by strengthening edges and corners (Brown 1986b) and the upperdeck, which is usually the weakest primary structure (Brown 1986b; Belcher 2008). Protection against underwater explosions can be increased by providing with a deeper inner bottom (Ferreiro and Stonehouse 1994) and selecting appropriate stiffener types and arrangements that could be based on simulation techniques (Bradbeer and Andrews 2012a; Bradbeer and Andrews 2012b). Moreover, structure should be allowed to deflect, which can then provide extra space around main structural elements as to not damage equipment (Heather 1990). WWII experience proved that the most highly stressed ships faced structural collapse problems; therefore a shallow amidships girder and an amidships break of forecastle should be avoided (Brown and Brown 1986; Brown 1990). Increased performance of longitudinally versus transversely framed ships was also observed, due to higher buckling strength (Brown and Brown 1986). Another vital structural design concept is that of structural continuity (e.g.: aligning superstructure bulkheads with main transverse watertight bulkheads) (Brown 1987; Chalmers 1993b). This minimises stress concentration points (Brown 1990) and vulnerability against shock and whipping (Chalmers 1993b), but introduces constraints on the layout (Brown 1987). Aluminium (which is often used for weight and maintenance reduction (Usher and Dorey 1982)) should generally be avoided in naval ship structures due to its low melting point (approximately 650^{o}C versus 1500^{o}C for steel (Usher and Dorey 1982)), good heat conduction properties (Carter 1988; Chalmers 1993b) and low fatigue strength leading to shattering under shock conditions (Manley 2012). As with commercial equipment, commercial structural standards (more vulnerable to blast and shock) are also increasingly being followed for cost cutting reasons (e.g.: HMS Ocean) (Martin 1998); although they would lead to weight escalations due to heavier plating and stiffeners required with increasing stiffener spacing, in order to maintain strength (Bradbeer and Andrews 2012b). Martin (1998) suggests that the cost savings could be invested in blast resistant structure and increasing ship size for greater separation; he also suggests that the aforementioned thicker, heavier commercial structure would be more efficient against fragments. An effective structural design style is that of longitudinal box girders (Chalmers 1993b; Robb et al 2010), demonstrated in Figure A25 and Figure A26.

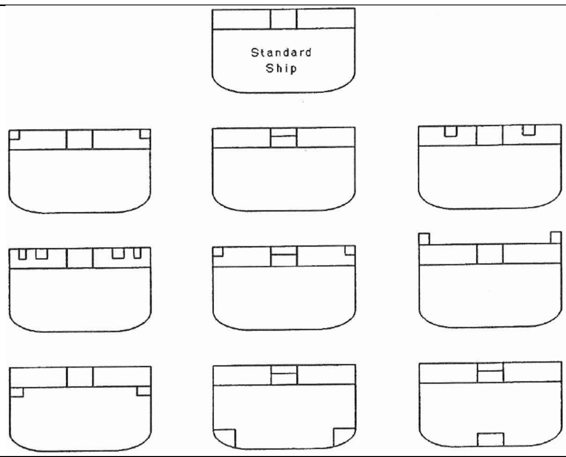


Figure A25: Possible Box-Girder Configurations (Chalmers 1993b)

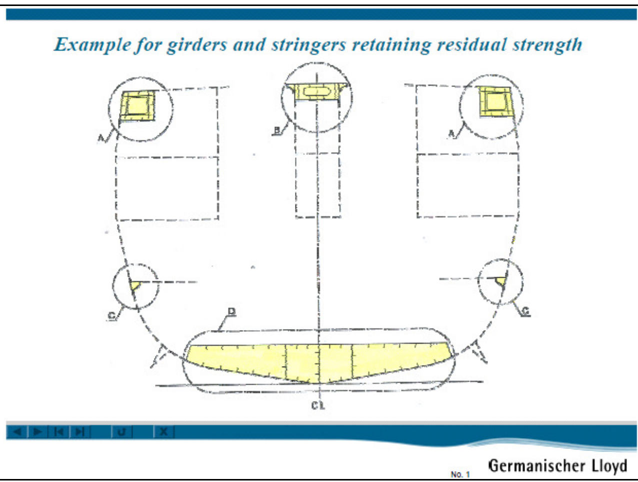


Figure A26: Example for Girders and Stringers Retaining Residual Strength (Petersen 2006)

The main concept is the incorporation of strong stiff longitudinal sections (Chalmers 1993b), which not only preserve structural strength after damage (Belcher 2008; Robb et al 2010) but also provide better protection to services running along the ship's length (Chalmers 1993b; Robb et al 2010).

Another major design aspect of ship vulnerability is its stability performance after damage (Boulougouris and Papanikolaou 2004). It is often claimed that the stability requirements have the greatest cost impact out of all survivability features on a warship (Knight 2012a; Knight 2012b). Foundering and capsizing due to flooding is countered through the inclusion of watertight subdivisions (bulkheads, collision bulkheads, vertical boundaries) (Surko 1994); the main vertical watertight boundaries of a frigate/destroyer type ship are shown in Figure A27.

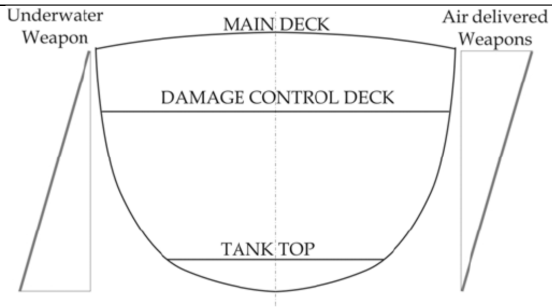


Figure A27: Vertical Watertight Boundaries (Boulougouris and Papanikolaou 2004)

Damage stability standards have been developed for naval and commercial ships in order to prevent sinking from typical flooding levels (Surko 1994). Naval standards are based on an analysis of reserve buoyancy – % length of hull open – and damage stability (Brown and Tupper 1989; Surko 1994). Figure A28 and Figure A29 present a comparison of length-of-damage and damage stability criteria for different navies.

	PATROL BOATS	SMALL WARSHIPS	LARGE WARSHIPS
Canada (C-03-001-024/MS-002)	< 30m 1 main compartment (min. 3m + 3% LBP)	30-90m 2 main compartments (min. 3m + 3% LBP)	>90m 15% LBP (min. 21m)
France (IT 6014)	< 30m 1 main compartment (min. 3m + 3% LBP)	30-90m 2 main compartments (min. 3m + 3% LBP)	>90m 15% LBP
Germany (BV 1033) Israel	< 30m 1 main compartment (min. 1.8m)	≥ 30m 18% LBP - 3.6m (not exceeding 18m)	
Italy (NAV-04-A013)	< 30m 20% LBP	30-95m 2 main compartments	> 95m 3 main compartments
Japan (S11003)		< 100m 2 compartments	> 100m 15% LBP
United Kingdom (NES 109)	< 30m 1 compartment	30-92m 2 main compartments (min. 6m each)	> 92m 15% LBP (min. 21m)
United States (DDS 079-1) Australia	< 100ft 1 compartment	100-300ft 2 compartments	> 300ft 15% LBP

Figure A28: Comparison of Length-of-Damage Criteria (Surko 1994)

	BUOYANCY	DAMAGED STABILITY
Canada (C-03-001-024/MS-002)	to 8cm (3.1in) margin line	list ≤ 15° in calm water $\theta_{max} = 45°$ progressive flooding or downflood angle $\theta_{roll} = 10°$ for 5000t ship A1 ≥ 1m-° (3.3ft-°) for 5000t ship A1 ≥ 1.4 A_2 with wind difference between GZ_{max} and wind heeling arm > 7.5cm (3.0in) GM_{fluid} ≥ 5cm (2in) at 0° heel
France (IT 6014)	to 7.6cm (3.0in) margin line	list ≤20° list ≤ 15° after cross-flooding $\theta_{max} = 45°$ $\theta_{roll} = 15°$ A1 ≥ 1m-° (3.3ft-°) for 5000t ship A1 ≥ 1.4 A_2 with wind difference between GZ_{max} and wind heeling arm > 8cm (3.1in)
Germany (BV 1033) Israel	to bulkhead deck	list ≤25° with 40kts wind $GZ_{residual}$ at θ_{ref} ≥ 5cm (2in) where $\theta_{ref} = 2\ \theta_{final} + 5°$
Italy (NAV-04-A013)	to 7.6cm (3.0in) margin line	list ≤15° in calm water θ at GZ_{max} > downflood angle $\theta_{max} = 45°$ A1 > 88m-t (290ft-t) for 5000t ship $GM_{transverse}$ > 0 in calm water
Japan (S11003)	to 50cm (19.7in) margin line	A_{ABC} ≥ 2 ABDE with wind $GZ_D \leq 0.6\ GZ_{max}$ with wind
United Kingdom (NES 109)	longitudinal trim must be less than that required to cause downflooding	list or loll < 20° in calm water $\theta_{max} = 45°$ or downflood angle $\theta_{roll} = 15°$ A_1 ≥1m-° (3.3ft-°) for 5000t ship A_1 ≥1.4 A_2 with wind $GZ_D \leq 0.6\ GZ_{max}$ with wind $GM_{longitudinal} > 0$
United States (DDS 079-1) Australia	to 3in margin line	list < 15° in calm water $\theta_{max} = 45°$ or downflood angle $\theta_{roll} = 10°$ for 5000t ship A1 ≥ 1.4 A_2 with wind
Notation:	θ = angle of heel A = work or energy	GM = metacentric height GZ = righting arm

Figure A29: Comparison of Damage Stability Criteria (Surko 1994)

Complete stability standards for RN surface ships are presented in (MOD 2000). Figure A30 describes the damage stability criteria for vessels to MOD standards with a military role.

(1) Angle of list or loll $<20^0$.

(2) GZ at point C <60% of maximum GZ.

(3) Area A_1: To be greater than the value given below for A_{min}:−

Δ = Displacement (tonnes)

For vessels of displacement less than or equal to 5000 tonnes.

$$A_{min} = 2.74x10^{-2} - 1.97x10^{-6}\Delta \quad \text{(m rad)}$$

For vessels of displacement greater than 5,000 tonnes but less than 50 000 tonnes.

$$A_{min} = 0.164\Delta^{-0.265} \quad \text{(m rad)}$$

For vessels of displacement greater than 50 000 tonnes consult the Sea Technology Group.

(4) Area A_1 >1.4 Area A_2.

(5) Longitudinal trim must be less than that required to cause downflooding.

(6) Longitudinal GM >0.

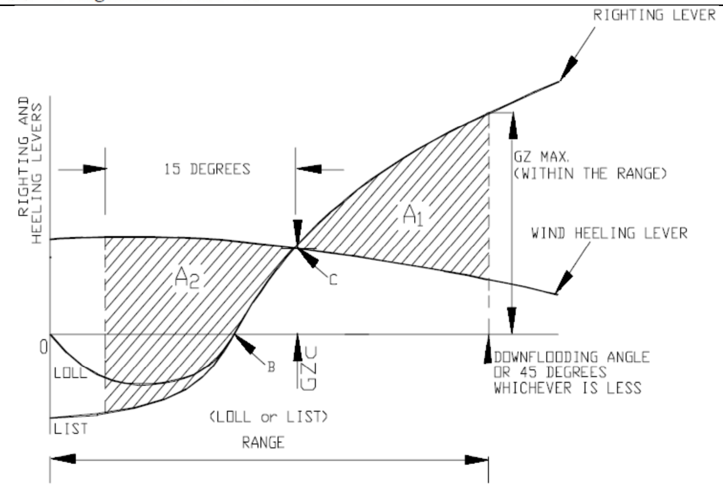


Figure A30: Damage Stability Criteria (MOD 2000)

It has been argued that current naval damage stability standards are outdated (based on WWII data), prescriptive and do not take into account modern threats (Surko 1994; Boulougouris and Papanikolaou 2012). These standards strongly determine the position of water tight subdivisions (Brown 1986b; Surko 1994) and therefore have a large impact on layout and weight (Boulougouris and Papanikolaou 2004). Trimaran side hull length is also driven by damage stability considerations, and should be approximately 40% of the ships overall length (Andrews 2004). Longitudinal bulkheads are generally avoided since they cause large heel angles and capsizing, as was observed with several Japanese and British WWII cruisers (Brown and Brown 1986). In addition, there were a number of occasions during WWII where the crew abandoned the ship once it heeled to an angle of about 15°, therefore quitting DC efforts (Surko 1994). Large heel angles and stability problems are also introduced when large quantities of water are used for firefighting, as on the USS Stark, although, in this case, no underwater damage occurred (Surko 1994). Ship stability can be improved through alterations in internal subdivisions, changes in operational profiles and stability standards, and addition of internal/external buoyancy fittings (Jasionowski et al 2007). For example WWII ships taken up from trade were fitted with empty drums to increase the reserve buoyancy (Brown and Brown 1986) and vehicle carriers have wing compartments to meet damage stability standards should the vehicle deck flood (Brown and Tupper 1989). Trimarans can be readily designed to achieve enhanced response to such damage, therefore, the extent of watertight subdivision could be reduced relative to monohull practice, reducing the imposed constraints on the layout; in addition, heel could be controlled after damage (e.g.: ship could be heeled away from damaged side) by flooding the unaffected side hull (Andrews and Hall 1995).

Zoning is a relatively new concept in naval ship design and it combines many of the features discussed above. The basis of this concept is the division of the ship into a number of autonomous zones (Brown 1990), typically 3-7 for most combatants (Ferreiro and Stonehouse 1994; Doerry 2007). This would improve the survivability of the ship's main functions (Brown 1987). Each zone could have its own prime mover and power unit (Brown 1986b), ventilation system (Brown 1986b; Martin 1998), living, cooking and bathroom facilities (Brown 1986b; Begg et al 1990;), chilled water unit, firefighting system (Begg et al 1990; Martin 1998), DC organisations, connectivity to the weather (Begg et al 1990; Ferreiro and Stonehouse 1994), etc. In addition, weapon systems are often concentrated in separate zones in order to enable 'fighting hurt' (Brown 1990; Martin 1998). However, in some cases, such as the accommodation compartments, it is expensive and impractical to apply a zoning style separation (Brown 1987). Also, before progress was made on IFEP systems, it was likely that two ship zones would have propulsion machinery (Brown 1993). Since it is expensive to duplicate systems within a zone, services are usually cross-connected to adjacent zones (Brown 1987). Brown (1987) also suggested that zoning may lead to larger and more expensive ships. However, costs may be saved due to shorter, simpler and easier to outfit (or even pre outfit) vertical service runs (Dicker 1986; Brown 1987). Zone boundaries are usually water/smoke tight and fire/blast/splinter resistant main transverse bulkheads (Covich 1988; Doerry 2007).

It has been argued that small, high speed and manoeuvrable ship are less susceptible (Harney 2010). However, larger ships can absorb more damage (as was observed with several super-tankers receiving ASM hits (Ling 1985; Phillips 1998)) and can be fitted with more defensive weapons (Brown 1997). However, it has been argued that whole fleet vulnerability may be reduced by procuring many cheaper ships rather than a few highly capable ones (Brown 1986b).

In conclusion, it is evident that due to the enhanced threats faced by modern warships, vulnerability reduction is an important aspect of the design phase (Ball and Calvano 1994). A variety of vulnerability reduction measures have been identified in order to counter diverse weapon effects. These measures, however, increase the complexity of design (Crow 2001).

A4.3 Recoverability Features

Four different ship kill definitions suggested by Ball and Calvano (1994) were previously listed. However due to the time element post hit, a certain level of damage may lead to another level, whether more severe or not (Ball and Calvano 1994; Papanikolaou and Boulougouris 1998). For example a damage system may be repaired by the crew, or progressive fire and flooding could lead to further damages placing the ship higher in the ship kill hierarchy (Ball and Calvano 1994). Therefore, the concept of recoverability must be considered in ship design as an integral part of survivability. The key recoverability pillars are given in Figure A31.

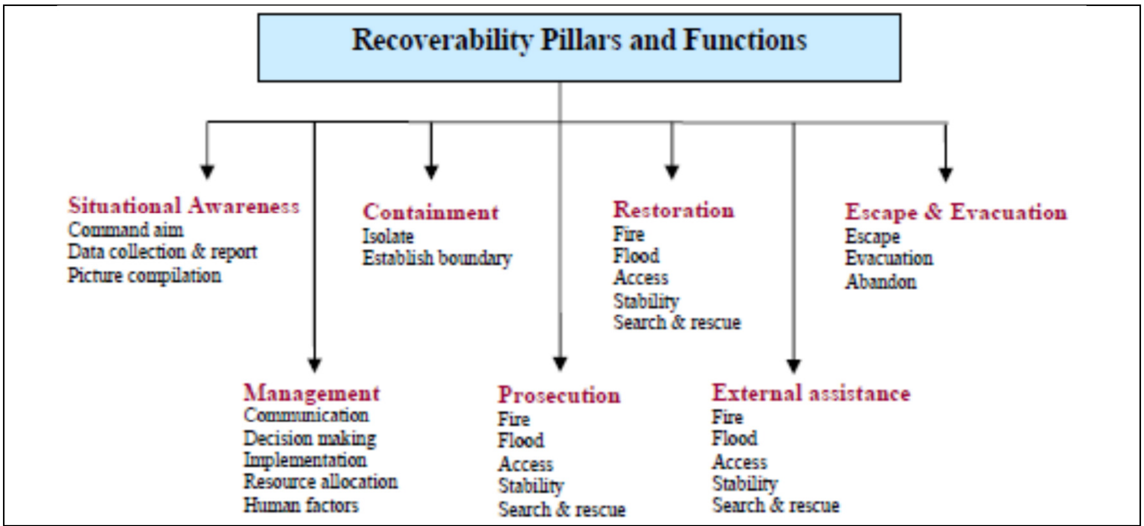


Figure A31: Recoverability Pillars (Bain 2006)

Primary weapon effects were defined in the previous section; however, when regarding recoverability, secondary weapon effects play a significant role. Secondary weapon effects occur in rapid secession to the weapon detonation (Said 1995). They include fire, smoke and toxic gasses (Herman and Loeser 1992), flooding (Martin 1998; Reese et al 1998), heat (Chalmers 1993b), physical damage to structure and equipment (Herman and Loeser 1992), etc. and extent of effects is heavily dependent on DC crew actions (Martin 1998). Such damage can lead to loss of buoyancy, stability, structural integrity, combat capability, mobility, protective systems, personnel and equipment (Herman and Loeser 1992). Missiles (unlike shells and bombs) often contain large quantities of unburned, highly flammable fuel (Brown 1986b) which is one of the main causes and/or enhancements of fire, smoke, etc. (Brown 1986b; Martin 1998). Hull penetrations below the waterline may cause flooding (Belcher 2008), as can the use of excessive water for firefighting (Clements and Kneebone 1985). In many commercial ships, such as tankers hit at the Gulf, these secondary effects are the main damage mechanisms, probably due to these ships having a much lower density of sensitive electronic equipment and low manning (Ling 1985). In fact, approximately 90% of the loss of life at sea is due to fire and flooding (the rest mainly due to intact stability loss) (Fireproof 2013).

Begg et al (1990) identifies two vulnerability reduction categories for naval ships; protection (previously defined) and counter action. Counter action includes limiting the spread of secondary effects through DCFF using automation and intelligent systems for co-ordination (Begg et al 1990). The objective of DC is to “achieve the highest potential for maintaining operational readiness and to preserve the warfighting capability of the ship, both in hostile and peacetime environments” (Herman and Loeser 1992). Procedures, ship design features and equipment designed to contain damage and restore systems are all essential DC issues (Herman and Loeser 1992). The crew’s DC response includes manual/automatic detection, immediate action (usually pre-planned), assessment of damage, containment of damage, priority setting by the CO (given internal and external situation) and finally restoration of systems (Clements and Kneebone 1985). Belcher (2008) states that DC is one of the main differences between commercial and naval ships. The priority for heavily damaged commercial ships is to have enough time for evacuation whereas for naval ships it is the restoration of capability (Belcher 2008). However, recently it has been argued that “large passenger ships should be designed for improved survivability based on the time-honoured principle that “a ship is its own best lifeboat”” (IMO 2011).

Past wartime experiences have taught many lessons regarding DC and have highlighted its importance. From WWII data it was concluded that DC effectiveness depends on environmental conditions, the danger of follow up attacks (which was also observed during the Falklands (Manley 2012)), crew experience, equipment available and effective communications (Brown and Brown 1986; Brown 1997). From the Falklands experiences it was concluded that DC was not well prioritised and cost reductions in that area would endanger crew and ships (Brown 1990). Several authors, such as Conklin (the DCA for USS Stark) (Conklin 1988) and Carter (1988) agree on that USS Stark (hit by two missiles while in the Gulf at 1987) was saved due to DC actions. A similar story can be told of the USS Samuel B. Roberts (hit by a mine in 1988) (Glass 1988). Conklin (1988) lists the almost immediate effects after the missile hits as dense smoke, intense fire, blocked access, numerous personnel casualties (a fifth of the frigates crew killed, many injured), lack of communications, and critical loss of forward firemain; he concludes that more DC equipment would be helpful. Conklin (1988) and Glass (1988) include illustrations summarising the damage received by these specific ships, shown below.

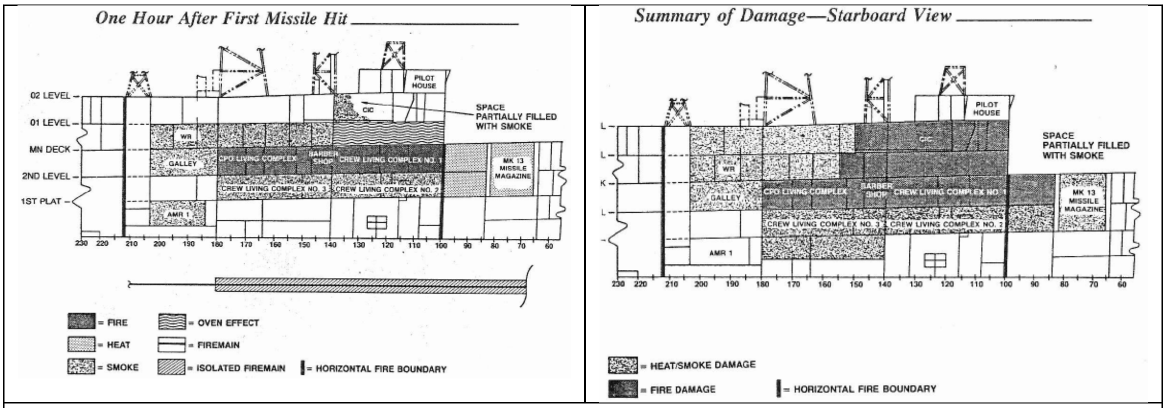


Figure A32: USS Stark Damage (Conklin 1988)

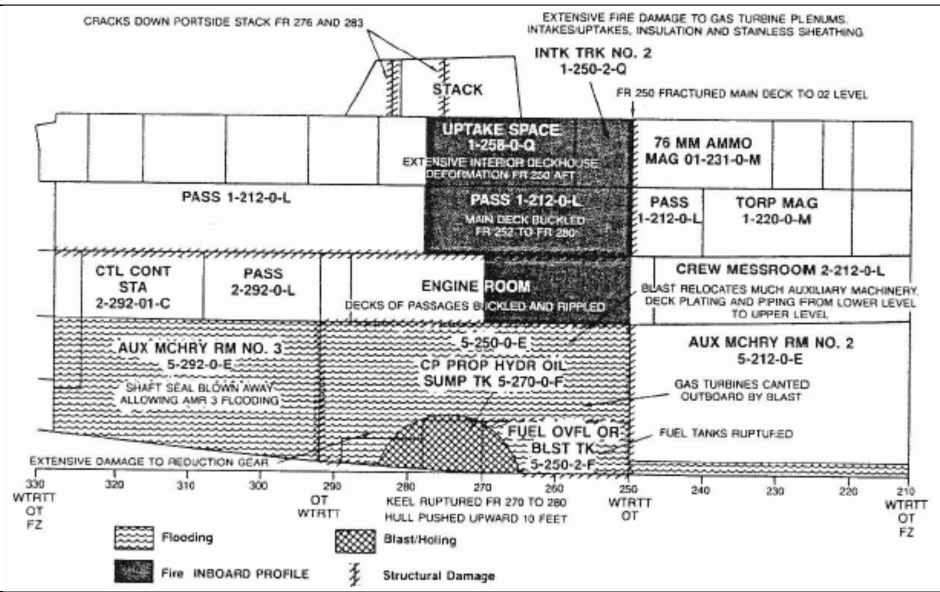


Figure A33: Underwater Explosion Damage to the Samuel B. Roberts (FFG-58) (Glass 1988)

An important aspect of recoverability and DC is maintaining an efficient and effective organisation (Herman and Loeser 1992). By allocating the appropriate manning and skill levels to the different ranks, defining conditions of readiness, regularly maintaining and inspecting equipment and training, means of detection, assessment and action against damage will be rapid and effective (Herman and Loeser 1992). Organisation centres should be duplicated and separated for effective co-ordination, and communication (Belcher 2008). Spaces dedicated to DC vary between navies. In RN ships, monitoring and control occurs through the SCC (which consists of NBCD Headquarters, also known as HQ1, MCR and emergency steering). An HQ2 is also provided for redundancy and is usually located at the bridge (Clements and Kneebone 1985; MOD 1988). This SCC arrangement, a layout of which is shown in Figure A34, allows easy communication between necessary DC and machinery control functions.

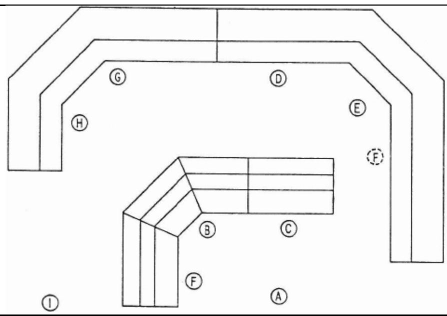


Figure A34: Current SCC Layout in a New Design Ship With Proposed Manning (see Figure A37) (Clements and Kneebone 1985)

A similar (combined HQ1, MCR and emergency steering) arrangement exists in Soviet destroyers, where HQ1 also serves as a secondary Operations Room (Wettern 1991). In addition, RN warships include FRPs operating from section bases which for a typical frigate would consist of one forward and one aft (Clements and Kneebone 1985). FRPs are in direct communication with HQ1 and are responsible for investigating damage and implementing DC actions (Clements and Kneebone 1985). Similarly, USN ships include the Damage Control Central (located in a protected area to provide shipwide DC coordination; it contains displays and communication facilities), Damage Control Repair Stations (several, for redundancy and ship coverage, are located on or above the DC deck and provide coordination for broad ship areas; they contain a display, communication facilities, DC tools and equipment), and other personnel stations, equipment lockers and decontamination spaces (Herman and Loeser 1992). Figure A35 shows how such spaces are spread around a combatant.

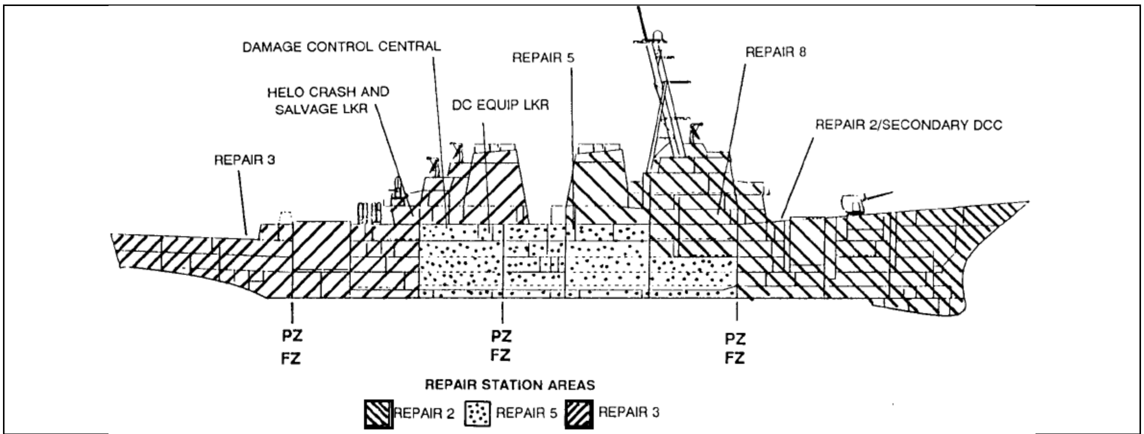


Figure A35: Damage Control Features (Herman and Loeser 1992)

In RN ships, overall DC responsibility and priority setting belongs to the CO, who is usually at the Operations Room or bridge (Clements and Kneebone 1985). He is in direct communication with the NBCDO (usually the MEO) located at HQ1, and the WEO located in the Operations Room. The NBCDOs responsibilities include DC co-ordination (damage state information, resource availability and allocation, containment and restoration actions, etc.), while the WEOs respectively is combat system availability (Clements and Kneebone 1985). Figure A36 depicts the RN organisational hierarchy and Figure A37 includes a proposed SCC manning for a new design.

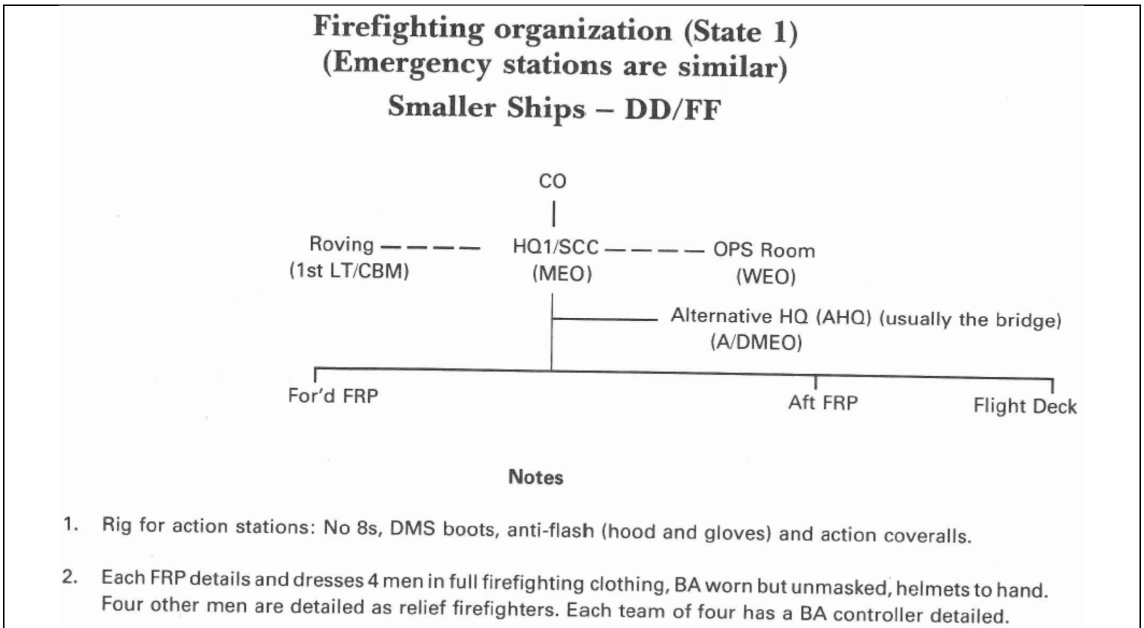


Figure A36: Firefighting Organization (State 1) – Smaller Ships (MOD 1988)

	Damage-control team position	Normal rank	Responsibility
A	Action NBCDO	MEO	All damage-control and machinery operations
B	Action NCBDO's assistant	Officer or Senior Rate	Damage-control coordinator
C	Marine Engineer Officer of the Watch	Senior Rate	Machinery coordinator
D	1st Panel Operator	Senior or Junior Rate	Propulsion and machinery operation
E	2nd Panel Operator	Senior Rate	Electrical coordinator
F	NBC Protection officer's assistant	WE Senior Rate	Specialist NBCD functions and assist 2nd Panel Operator
G	Incident Board Operator 1	Junior Rate	—
H	Incident Board Operator 2	Junior Rate	—
I	Messengers	2 Junior Rates	—

Figure A37: Proposed SCC Manning For a New Design (Clements and Kneebone 1985)

In contrast, in USN ships, DC responsibility relies on the XO and CHENG (Glass 1988). However, the XO is primarily concerned with "second-in-command type issues" and the CHENG with propulsion issues, therefore leaving DC issues to the DCA (Glass 1988). The DCA is usually an inexperienced junior rate with important and demanding responsibilities (including DC and repair, manning issues, training, etc.); therefore, Glass (1988) suggests increasing the grade and experience of that officer.

Another important aspect of DC is training in order to prepare the crew for emergency situations and provide them with skills regarding the operation of equipment (Herman and Loeser 1992). Training occurs both on ships and on land using simulators and simulation tools and should be as realistic as possible (Herman and Loeser 1992). Glass (1988) supports that the effective DC actions which saved the USS Samuel B. Roberts were a direct consequence of good training (which led to effective command and internal organisation and the ability for parties to operate autonomously in a dynamic situation). Conklin (1988) also states that good training of the crew of USS Stark led to rapid DC party formation and employment. However factors such as choking smoke, intense fire heat, hot water and steam produced, large list angles, crew dehydration, fatigue and psychological shock, casualties and injuries, which all occurred during the USS Stark incident and lasted over 24hr, cannot be realistically simulated (Conklin 1988).

After an incident occurs one of the main priorities is to contain its effects. For example, after being hit, the DC crew of the USS Stark set and maintained fire boundaries to isolate the hit portion (middle third) of the ship (Conklin 1988). Watertight bulkheads and decks (in addition to restricting primary weapon effects, such as blast and fragments (Brown 1990)) can also limit the spread of secondary effects such as fire, smoke and flooding (Andrews and Brown 1982; Reese et al 1998) or even NBC contamination (Brown 1987), although primary damage to WT doors and bulkheads limited secondary damage containment during the Falklands conflict (Manley 2012). Subdivisions can be constructed from composite materials which limit fire spread (in addition to being lighter and needing less maintenance than steel, although their blast performance is inferior) (Bebbington and Groves 2006). Boundary cooling is another method often used to prevent fire spread (Brown 1990). A combatant's main boundaries are the DC deck, main deck, double bottom and transverse bulkheads as shown in Figure A38.

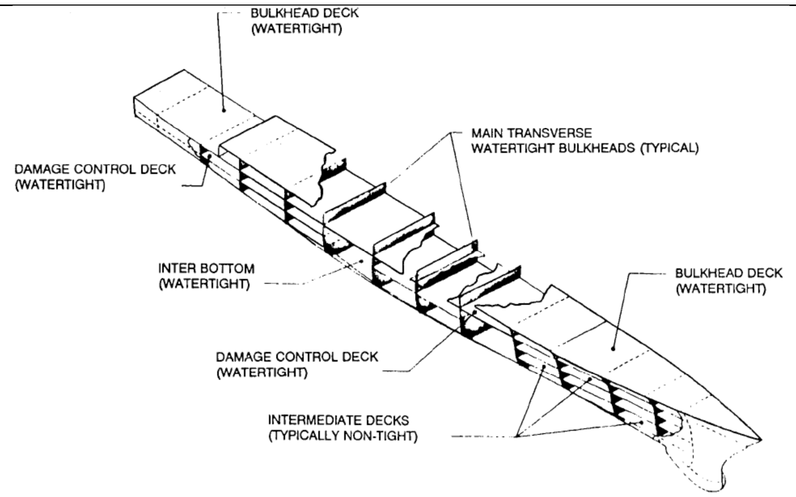


Figure A38: Watertight Bulkhead and Deck Locations (Herman and Loeser 1992)

According to Brown (1986b), the addition of extra bulkheads can be expensive due to the increase in ship length (approximately 1m per bulkhead) and the cost of making penetrations and doors fire/smoke/water tight. Also, the cost of a bulkhead depends on its location, amidships being most expensive (Brown 1986b). Zoning presents clear advantages in containing secondary weapon effects. Ideally they should be autonomous, with independent power generation units for necessary equipment, ventilation systems to mitigate smoke spread and their boundaries should be fire/flood proof to prevent damage spread to adjacent zones (Brown 1987; Brown and Tupper 1989). Moreover, zones can be able to prevent the spread of NBC contamination and each should contain separate DC equipment (Belcher 2008). After damage is confined to a single zone, if it is not sufficiently recovered it may be evacuated; however, the remaining ship zones should still be functioning (Brown 1986b). The concept of CPS (demonstrated in Figure A39) was adopted by the USN to provide an uncontaminated environment to selected zones of the ship (Herman and Loeser 1992).

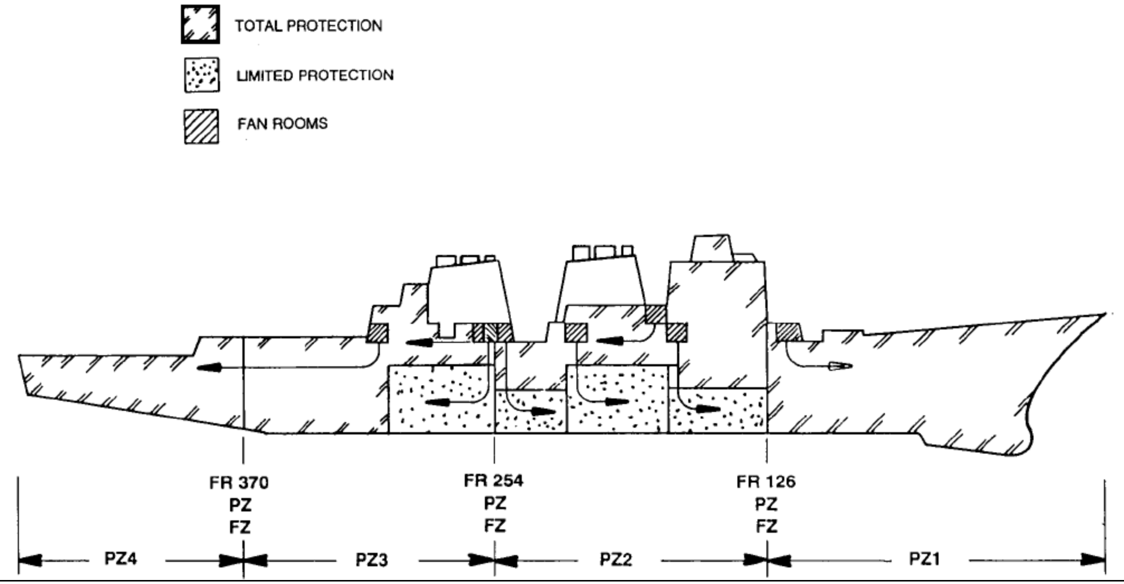


Figure A39: Full-Time Collective Protection System (CPS) (Herman and Loeser 1992)

Containment of incidents depends, to a large extent, on the layout of the ship. An effective layout also affects other recoverability issues such as personnel flow. Good access, especially on the DC deck (usually No 2 Deck on frigates), is vital for DC effectiveness and for evacuation (Brown 1986b). Also, below the DC deck there are no doors through watertight bulkheads and bulkhead penetrations are minimised; therefore the DC deck has to be fire/smoke/watertight to enable good personnel flow (Brown and Tupper 1989; Brown 1990). Access below the DC deck is provided into each water tight compartment that has ready access by two widely separated hatches (Brown 1990). Access routes must be unobstructed and include emergency lighting and escape route indications, possibly by means of thermoluminescent paint (Brown 1989; Manley 2012). Alternative escape arrangements must also be provided in case main passageways are blocked, a challenging aspect for smaller vessels (Brown 1989). In conclusion, a further constraint is introduced in the layout development of naval ships since both the limitation of weapon effects and the need to provide sufficient access for DC crews and evacuation must be satisfied (Brown 1987; Herman and Loeser 1992). Heather (1990) considers incorporating two main passageways on either side and different decks, while Begg et al (1990) designed a ‘resilient frigate’ with a five-deck deep hull and minimal superstructure, therefore, providing a relatively clear upperdeck and two access decks for improved DC personnel flow. Another layout related recoverability feature of naval ships is the redundancy and separation of vital equipment (the distribution of which is of great significance), services (pipes and cables) and FRP section bases (in addition to the DC co-ordination centres mentioned previously) (Herman and Loeser 1992). Another useful feature would be to reduce the exposed cross-sectional area of the above systems (Herman and Loeser 1992). Because of the developed fire, the crew of the USS Stark had access to only one of the three DC lockers, highlighting the importance of redundancy and separation and of access arrangements (Conklin 1988).

DC equipment is essential for recoverability. This was frequently demonstrated in WWII (Brown and Brown 1986) as well as in the USS Stark (Conklin 1988) and USS Samuel B. Roberts (Glass 1988) incidents. Akin to escape routes, DC equipment must also be clearly indicated through thermoluminescent paint or other suitable methods (Brown 1990) and should be positioned in proximity to ship entrances for external access (Heather 1990). Existing DC equipment is aimed at dealing with the effects of NBC contamination, fire, flooding, smoke, system disruption, compromise of boundary integrity, hypothermia, drowning, fragmentation and projectiles effects (Herman and Loeser 1992) and need to be inspected and maintained (Brown 1989). Herman and Loeser (1992) state that such equipment must be designed to provide maximum capability, safety of operation, portability, long shelf life, lightweight and minimal size, minimum number of sizes, minimum procurement time, simplicity, multiple use, have compatibility of operating fluids, commercial availability if possible, complete technical documentation and instructions, fire retardant of materials and minimum disruption to personnel performance.

Fire at sea is the most frequent hazard that ships encounter (Azzi et al 2011). Fire is regarded as one of the most destructive situations for both commercial and naval vessels causing life loss and expensive damaged (Ling 1985; Truver 2001), although it has been observed that fires caused by action damage are more intense (Manley 2012). Most severe fires involve fuel and thus especially important to AMVs which usually include powerful engines and large fuel quantities in relatively small hulls and often have aluminium structures (Brown 1989). The possibility of fire in naval ships has increased since WWII due to the lower flash point of modern fuels and the difficulty in extinguishing rocket fuels (Brown and Brown 1986). Relatively recent examples of fire incidents on naval ships include the HMS Sheffield (hit at the Falklands in 1982 by two ASMs at close range with a large quantity of remaining fuel) where the burning of bulkhead coatings produced toxic smoke, therefore, leading to inability of fire containment which contributed to the ship being lost (Truver 2001; Crees 2009). In fact, fire was one of the major causes of damage on ships during the Falklands Conflict (Manley 2012). Another incident is that of the USS Stark where smoke and fire which was caused by rocket fuel and burned at temperatures of over 1,900^{o}C, nearly double the assumed upper limit for ship fires, instantly igniting combustible materials and melting (aluminium) structure, lead to 37 deaths (Conklin 1988; Truver 2001). After 2hrs neighbouring compartments also ignited due to the excessive heat (Conklin 1988). The first step in fire protection should be prevention, through avoiding use of flammable and smoke generating material (Ling 1985; Belcher 2008) especially at passageways (Brown 1990), regular maintenance of fuel systems (Brown 1989), safe stowage of unavoidable combustible substances (Brown 1990). Brown and Tupper (1989) estimated that a typical frigate contains approximately 45te of ammunition, 700te of diesel and 100te of other combustible material. The next steps are to detect the fire with no delay and prevent it from spreading (Brown 1989). Fire can rapidly spread by igniting paint, concurrently generating smoke and toxic gases, and heat levels can ignite adjacent compartments (Truver 2001). The avoidance of material with low melting points and ready heat conduction properties, such as Aluminium, and the use of composites with insulation properties and limited smoke generation, which when burned limits fire and smoke spread, is recommended (Brown 1989). In addition, techniques such as boundary cooling and employing smoke barriers are employed (Brown 1990). The final step would be to extinguish the fire with the aid of specialised equipment (Ling 1985; Brown 1986b). However, such equipment is often damaged due to weapons effects, therefore, the distribution of the equipment along the ship is essential (Manley 2012). Firefighting equipment includes portable equipment, suits, helmets, boots, flash hoods, thermal imagers, breathing apparatus and goggles (Herman and Loeser 1992). Smoke control equipment consists of smoke removal fans, portable smoke curtains and blankets, etc. (Herman and Loeser 1992). Figure A40 shows a typical firefighting rig.

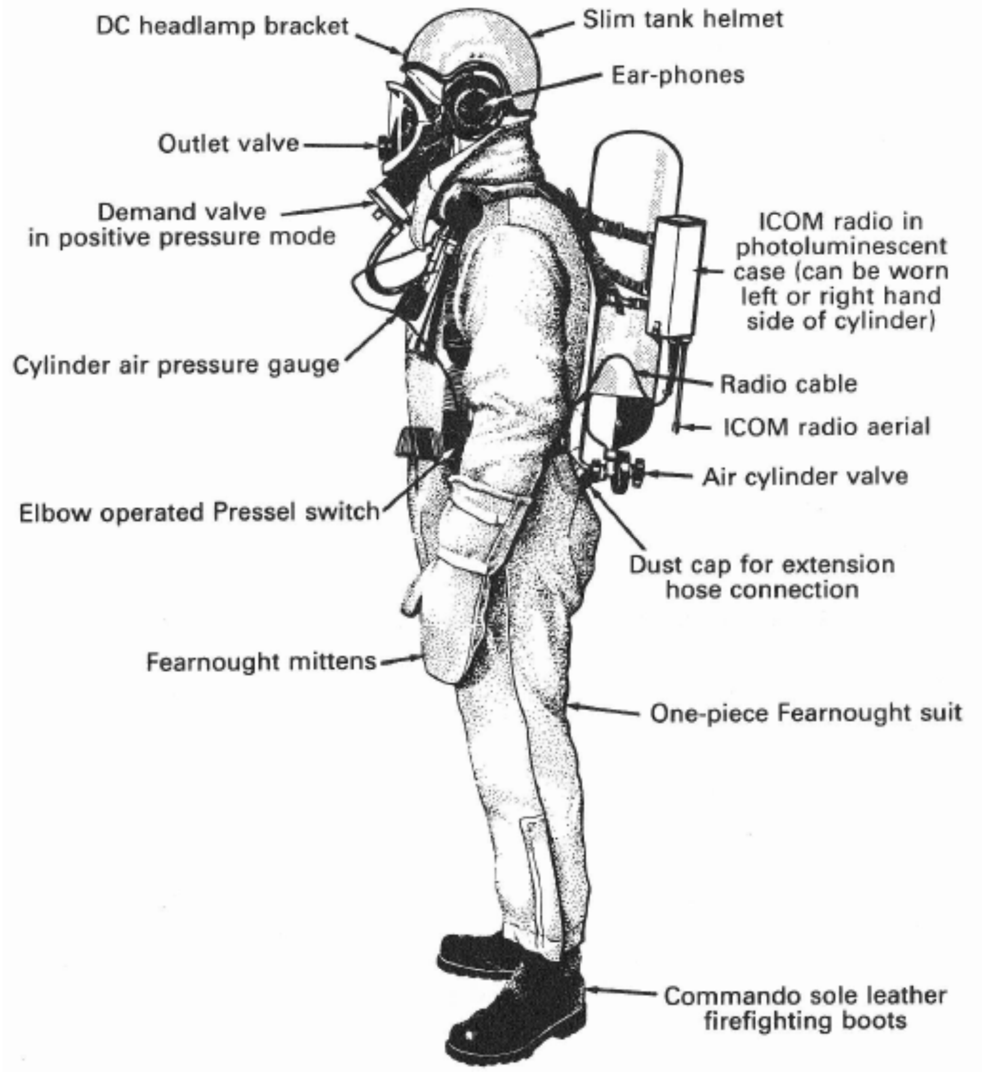


Figure A40: Full Firefighting Rig (MOD 1988)

To aid fire prevention and fighting MOD published a Guide to Ship Firefighting (MOD 1988), containing simplified information on causes of fire, fire prevention, firefighting, procedures and equipment (including illustrations), tactics and techniques. The book is given to new entry personnel, during firefighting courses and copies are kept in all naval vessels (MOD 1988).

A further hazard to ship survivability is flooding, occurring through hull breaches and/or excessive firefighting water (leading to stability problems) (Belcher 2008; Manley 2012). The USS Stark listed by more than 16^{o} as a consequence of a ruptured firemain and the use of water for firefighting, therefore, increasing the difficulty of DC actions (Conklin 1988). Eventually, holes were drilled on the exterior sides in order to drain the water (Conklin 1988). The effects of flooding may be limited through correct subdivision and by limiting bulkhead penetrations below the waterline (Brown 1987). Flood management is achieved with equipment such as automatic and portable pumps (Herman and Loeser 1992; Belcher 2008), installed dewatering systems (Reese et al 1998), tools and equipment for plugging holes and shoring bulkheads, e.g.: timber (Wettern 1991; Belcher 2008). Wet and dry suits and life vest protect from hypothermia and drowning (Herman and Loeser 1992).

NBC contamination is a further threat that naval ships have to deal with. In order for a ship to function in a contaminated environment, it should be fully operable while sealed from the atmosphere (Brown and Tupper 1989). The citadel boundary is air tight (with minimum openings (Herman and Loeser 1992)) and air, required to maintain a positive internal pressure, filtered (Brown and Tupper 1989). External access should be provided through cleansing stations (Brown and Tupper 1989), such the one illustrated in Figure A41.

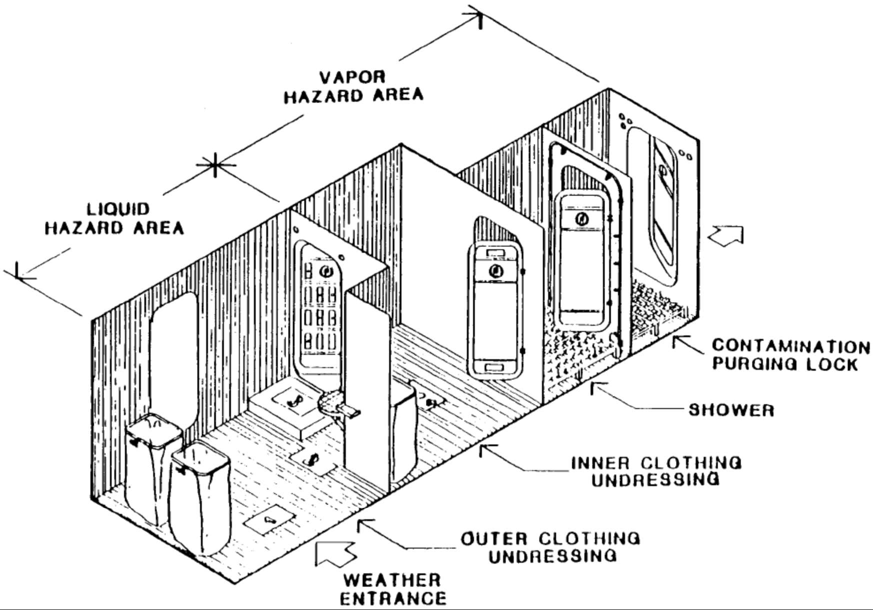


Figure A41: Personnel Decontamination Station (Herman and Loeser 1992)

Moreover, a topside water washdown system should be installed and protective clothing and breathing, and detection apparatus (including masks, suits, gloves, boots, detector paper, drinking aids, detection kits, breathing equipment, etc.) should be available to the DC crew inspecting the topside (Herman and Loeser 1992). Figure A42 shows typical chemical protective clothing.

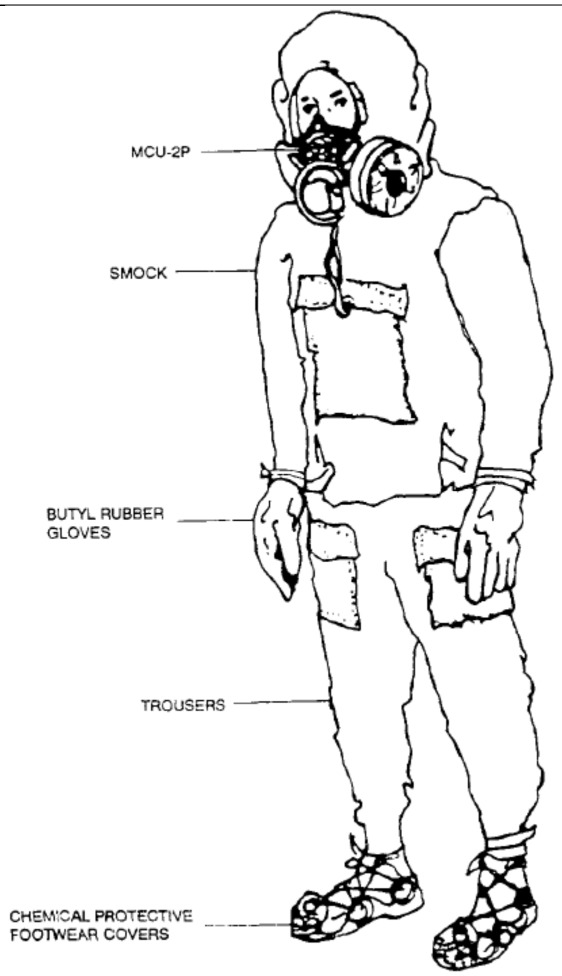


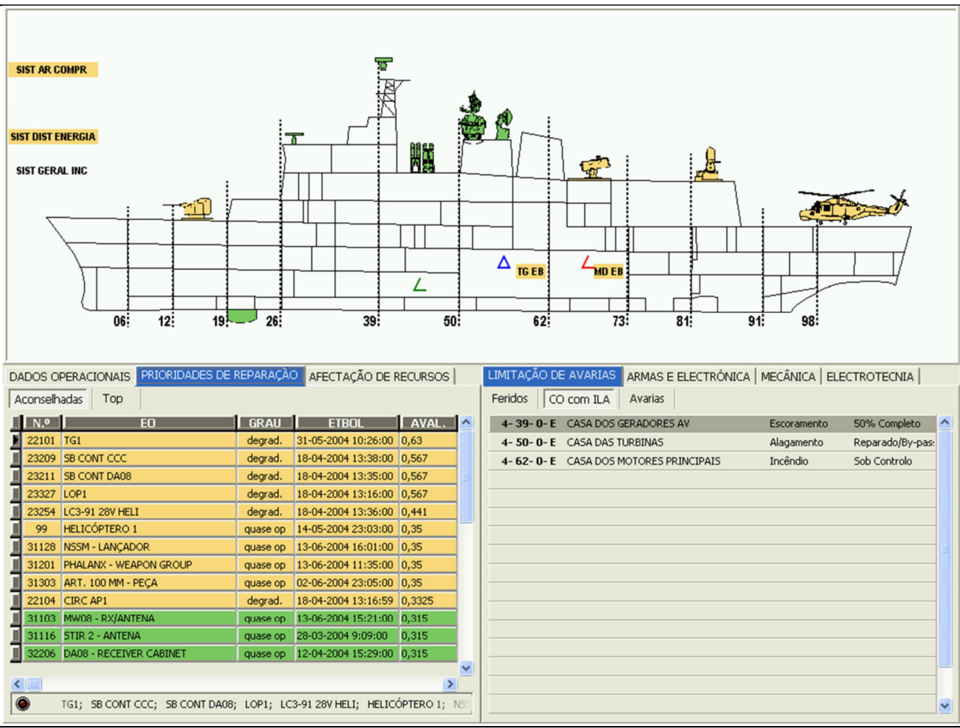
Figure A42: Chemical Protective Overgarment (Herman and Loeser 1992)

From both WWII and Falklands Conflict experiences it was found that DC relies excessively on effective voice communications (Clements and Kneebone 1985; Brown and Brown 1986). However, it was also concluded that most DC related problems during the Falklands Conflict were caused by inadequate information which led to the need to reduce reliance on manual techniques and voice communications was identified (Clements and Kneebone 1985; Manley 2012). DC teams require portable communication equipment, including emergency backup facilities, which should be resistant to smoke and heat (Clements and Kneebone 1985; Belcher 2008). Robb et al (2010) suggested that low power Wi-Fi systems would improve communications, therefore reducing decision making time, and could be installed in a ship at any time in its life at low cost.

Reductions in crew sizes have had a significant impact on ship DC and system recoverability (Clements and Kneebone 1985; Reese et al 1998). Smaller crews may lead to fewer casualties, as is the case with some commercial ships (Ling 1985), but will also decrease the capability of recovering and fighting hurt (Reese et al 1998) since for a typical frigate the management of the DC organisation requires approximately 15-20 people (Geertsma et al 2012). However, these tendencies may be partially countered through technology developments and increased automation and remote sensors in all naval ship attributes, including DC (Clements and Kneebone 1985; Truver 2001). Begg et al (1990) identifies three main DC stages, immediate action, subsequent counteraction and long term correction, and suggests the first two rely on automation to a large extent. Automatic systems also have the advantage of rapidly detecting hazards, such as fire (Brown 1989). However, increased automation leads to more complex systems (Gates and Rusling 1982) which may be damaged by primary weapon effects, and therefore should be complemented by human intervention (Belcher 2008). Automatic DC systems fitted to modern combatants include automatic fire, smoke and flooding detectors, automatic firefighting systems (such as sprinklers, water-mist systems, foam systems and CO_2 systems for unmanned spaces) (Clements and Kneebone 1985; Belcher 2008), automatic flood control systems (Clements and Kneebone 1985; Edwards and Carr 1998), fixed boundary cooling systems (Edwards and Carr 1998), gas-drenching systems for machinery spaces, automatic surveillance of doors, remote control of fire pump valves and ventilation systems (Clements and Kneebone 1985), magazine flash suppression systems (Clements and Kneebone 1985; Harney 2010). Systems were fitted to RN ships after experiences from the Falklands, in order to reduce dependence on manual techniques and the associated problems (Clements and Kneebone 1985). Edwards and Carr (1998) proposed an early design stage methodology examining optimum, cost-effective man-machine balance for DC. Bodegraven et al (2012) describe the DINCS project which is aimed at automating the task of rerouting redundant systems components after damage (e.g. pipes and cables in the electrical, chilled water, firefighting, propulsion and steering systems, etc., on which operation of combat systems, control of damage and ship's mobility depend). Such tasks are usually performed by crew members often under chaotic circumstances and under the pressures of complex marine systems, rapid reaction times and reduced crew sizes. During the initial phase of the project, DINCS technology was demonstrated on a chilled water system (Bodegraven et al 2012). Robb et al (2010) considered the inclusion of automatic fire/smoke detection and extinguishing systems and CCTV in a frigate would be of minimal cost.

Recent technological improvements have also led to the development of decision support systems (Edwards and Carr 1998). Such systems aim to reduce human errors and speed up decision making after damage by providing advice to the operator under extremely demanding conditions (Bastisch 2002; Lee et al 2002). Lee et al (2002) presented a knowledge-based response system that assisted DC personnel in regard to damage to the pressure hull and piping system in a submarine. The domain knowledge was obtained from design documents, design expertise and interviews with operators and data was fed from users, sensors, and external computer programs. Bole (2007) suggests structural assessment tools are installed onboard (as is Seagoing Paramarine for stability assessment); these can assist with incidents such as groundings. Such a development would allow the crew to assess the damage and decide on whether to commence repair actions or abandon the due to structural failure being deemed catastrophic. It would also avoid the complications faced during the HMS Nottingham grounding of the coast of Australia in July 2002, where calculations had to be carried out in the UK with limited information available (Bole 2007). Bastisch (2002) described an Integrated

Platform Monitoring and Control System, which includes a BDCS module, for the German F124 AAW frigates. The BDCS provides the operator with automatic damage reports, monitoring of ship closure states, fire and flooding incidents and DC defence measures. Its main functions are to acquire data from sensors, inform the operator and trigger an automatic response. However, the operator is still essential to avoid inappropriate actions being made by the BDCS. A similar system is SINGRAR of the Portuguese Navy (Sarmento and Duarte 2005). This is a decision support system with an equipment repair tool, which combines information from the external battle (e.g.: ASW, ASuW, AAW, ASyW) and internal battle (e.g.: ship's weapons & electronics, propulsion & power plant, NBCD, medical, etc.). A typical decision support screen of SINGRAR is replicated below.



Information on sensor weapons, damage control, propulsion and power plant displayed (Sarmento and Duarte 2005):

- Top panel presents affected items with a colour code to show the relevance of the equipment for the tasks that the ship is involved with.
- Bottom left panel has a list of equipment needing repair ranked by priority according to the operational scenario, and again colour coded for relevance.

All this information is colour coded in order to focus the decision maker attention into the failures which are considered more critical (Sarmento and Duarte 2005).

Figure A43: SINGRAR Decision Support Screen (Sarmento and Duarte 2005)

Geertsma et al (2012) describe the PMS of the radically lean manned (with a crew of 50) Holland-class Patrol Vessels of the RNN. The PMS includes a FFDC system which is aimed at taking advantage of automation technology in order support the small crew in DCFF through the four main tasks identified by (Geertsma et al 2012), i.e. gathering and assessing information (on, for example, fire detectors, doors and hatches, etc., to increase situational awareness), decision making and acting (through containing a number of predefined procedures for various incidents). It is also aimed at reducing errors from operator stress and reducing time for information gathering and exchange. Ellison and Escott (2012) and Harold et al (2012) however, criticise the problematic requirement definition and capturing of such systems (augmented by the dissimilar perceptions between contractors and customers (Harold et al 2012)) and describe the experiences gained through the design of the IPMSs of the new RN Queen Elizabeth Class Aircraft Carriers and modernised RCN Halifax Class Frigate respectively. Given that the IPMS "is responsible for the management, control and surveillance of the state of the ship services and machinery" (Ellison and Escott 2012), deficiencies in such systems could prove critical.

The ability to recover systems after damage is a vital element of recoverability. One of the principal responses of the USS Starks DC crew was to restore the integrity of the damaged forward firemain, which had introduced flooding and threatened ship stability (Conklin 1988). After the secondary weapon effects of an incident are managed, damaged systems may be recovered by re-routing services through undamaged ship sections, emergency structural repairs, bringing systems back on line (Martin 1998). These actions are highly dependent on the ship and system layout (Martin 1998). Electrical power has to be generated and distributed for weapon and propulsion systems (Cerminara and Kotacka 1990). Therefore, Cerminara and Kotacka (1990) considered maintenance of DC and recoverability to be a major design principle for electrical systems (i.e.: such systems should be designed to constantly provide an acceptable level). Systems should be designed to function after a hit (Ball and Calvano 1994) by, for example, isolating damaged sections and self-reconfiguring (Edwards and Carr 1998; Manley 2012). However, since this is not always possible, spare parts (a deficiency of which was observed during the Falklands conflict (Manley 2012)) are necessary for system recovery (Herman and Loeser 1992).

Another important aspect of naval ship recoverability is external assistance (Rogers 1988). This aspect is of increasing importance when considering blue water warfare (Rogers 1988). USN forward deployed ship salvage and repair forces were present during WWII in order to minimise the incidents of damaged ships returning to their bases for extensive repair and recovery (Rogers 1988). Rogers (1988) claims that repair base priorities include stabilising the damage, removing the vessel’s hazards and restoring its capability. External assistance (from other ships or repair bases) should include extra firefighting equipment, pumps, auxiliary power units, explosive ordnance disposal specialists, portable communication gear, medical repair teams, specialised repair assistance, damage-assessment team, availability of basic materials (spares), skilled metal trades and portable outboard propulsion units (Rogers 1988). In the case of the USS Stark, oxygen apparatus, drinking water and fuel for pumps were eventually exhausted (Conklin 1988). External assistance arrived from other ships, leading to the ship being salvaged (Conklin 1988; Rogers 1988). The USS Samuel B. Roberts also received external assistance contributing to its rescue, whilst the HMS Sheffield which did not (due to the force still being under threat at sea), eventually foundered (Rogers 1988). In addition, an approach towards the recovery of damaged systems in modular ships could be to provide modular weapon and electronic systems by other ships and/or repair bases (Rogers 1988). An example of a modular ship is illustrated in Figure A44.

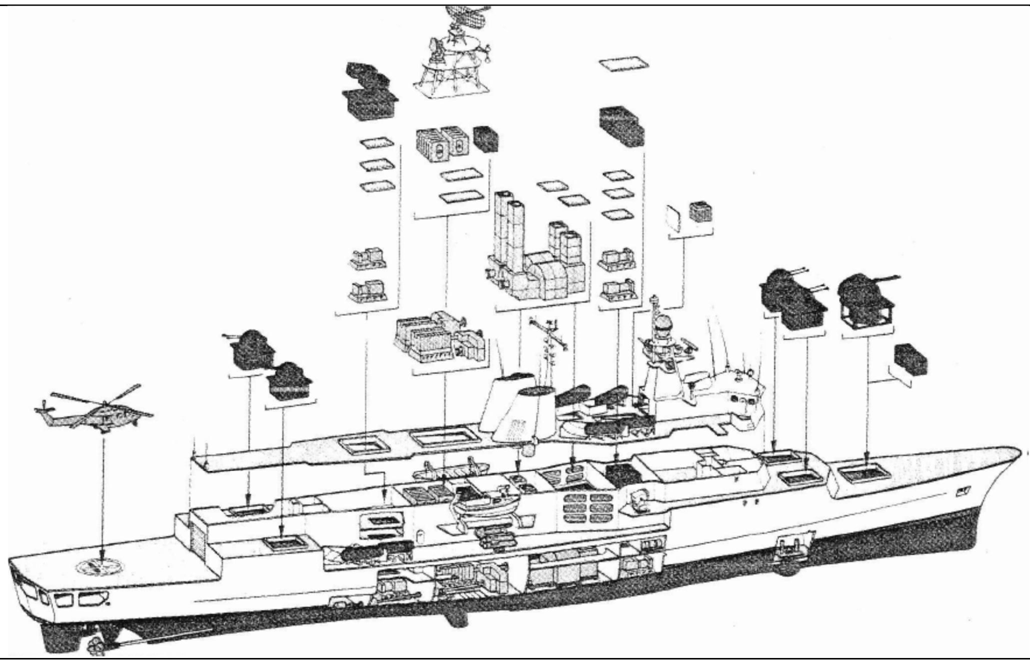


Figure A44: Modular Weapon and Electronic Systems and Palletized Operator and Display Consoles, such as those Featured in the West German MEKO Frigates, Facilitate Rapid, Inexpensive Damage Repair both in Forward Areas and Domestic Shipyards (Rogers 1988)

The importance of recoverability in ship design has led to the formulation of rules and regulations. Thus the Rules for Classification and Construction by Germanischer Lloyd include integrated survivability management tools, structural fire protection standards, NBC protection standards, etc. (Petersen 2006). The IMO has developed safety standards for the construction, equipment and operation of commercial ships under the SOLAS convention (IMO 2004). SOLAS includes, for example, fire-protection standards developed following several incidents involving commercial ships; such standards cover structural fire-protection systems on bulkheads and overhead spaces, limiting flame spread characteristics for surfaces, smoke and toxic material generation of paints, installation of smoke/fire detection equipment, installation of remotely controlled fire doors, etc. (Truver 2001). In addition, NATO published the Naval Ship Code safety standards (NATO 2011), as the naval equivalent of the commercial SOLAS. The Naval Ship Code (NATO 2011) includes chapters on structure, stability, fire safety, escape, evacuation and rescue, etc. However, when considering novel designs and innovative layouts, it is difficult to satisfy existing, prescriptive rules for safety (Azzi et al 2011; Vassalos 2012). Azzi et al (2011) suggest that simulation is the answer to such limitations. Brown (1989), on the other hand, supports for novel ship design, where data is sparse, compliance with legislation is a minimum. Barton (2009) analysed RN ship data from WWII and the Falklands and concluded that ships have the tendency to either sink quickly (under 30mins) or slowly (over 2hrs); see Figure A45.

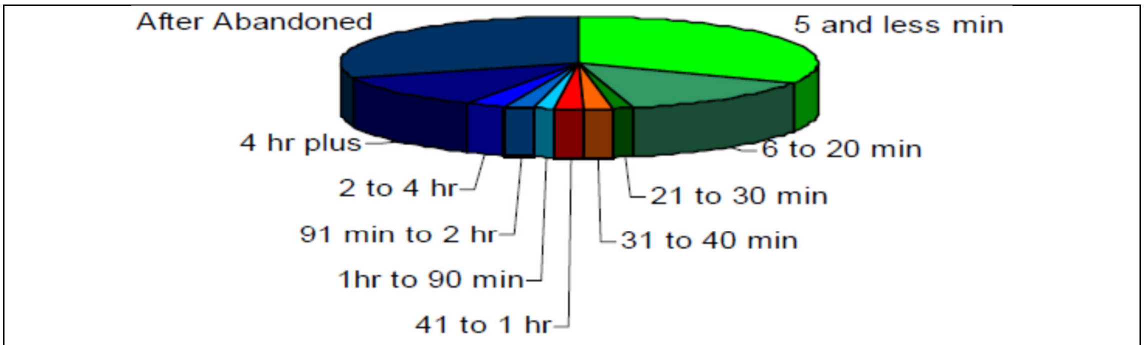


Figure A45: Vessels With Known Sinking Times in WWII (Barton 2009)

Barton (2009) therefore suggests that rules considering vessel evacuation should include two scenarios, rapid sinking (providing many means of escape, such as float free life rafts, life jackets near exits) and slow/safe/orderly evacuation where possibly some of the crew could abandon early leaving others to attempt and manage the situation).

Significant resources, in terms of crew, equipment and funds have to be allocated to DC (Belcher 2008). DC is one of the main drivers of complement size in warships which in turn is a major driver of the UPC (e.g.: space and services provided) and TLC (e.g.: crew costs) (Edwards and Carr 1998; Martin 2007). Martin (2007) estimated that recoverability measures in a frigate account for approximately 7% of the UPC, however, with a significant uncertainty. He concluded that automation is attractive for complement and cost reductions, but simulation techniques are essential to achieve an effective balance of crew and automation.

In conclusion, recoverability is difficult to provision since it is influenced by designers, personnel planners and the ship's crew, who all have different objectives (Edwards and Carr 1998). DC is heavily reliant on the ship's crew, necessary equipment and resources, set priorities, technology, procedures and training (Edwards and Carr 1998). Its dynamic nature increases its complexity and is hard to manage (Edwards and Carr 1998). Certain novel ship types, can introduce benefits in the area of recoverability due to a range of characteristics (e.g.: the trimaran has the ability to heel the ship away from the damaged side) (Andrews and Zhang 1995).

Appendix 5: An Integrated Approach to Naval Ship Survivability in Preliminary Ship Design (RINA Warship 2012)

An Integrated Approach to Naval Ship Survivability in Preliminary Ship Design

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SUMMARY

The rising cost of warship procurement, coupled with declining defence budgets, has led to a reduction in the number of ships in most western navies. One way to deal with this situation is be innovative in both the design process and exploring specific ship options, especially at the crucial early design stages. Moreover, cost cutting has often focused on aspects which are difficult to quantify, such as survivability. Computer technology can be utilised to exploit architecturally orientated preliminary design approaches which can address innovation in both the above aspects and in issues such as survivability early in the ship design process.

A number of survivability assessment tools currently exist; however, most fail to integrate all survivability constituents (susceptibility, vulnerability and recoverability), in that they are unable to balance between the component features of survivability. Some of these tools addressed survivability qualitatively, and are therefore less than ideal for requirement specification, others are aimed towards the detailed design stages where implementing changes is heavily constrained.

In this paper, a simple, rapid method for better integrating and quantifying survivability in early stage ship design is proposed using the UCL derived Design Building Block approach.

NOMENCLATURE

ASM	Anti-ship Missile
ATU	Air Treatment Unit
CAD	Computer Aided Design
CASD	Computer Aided Ship Design
CIWS	Close-in Weapon System
CSEE	Combat Systems Effectiveness Exercise (specifically used at UCL)
CWP	Chilled Water Plant
DBB	Design Building Block
DC	Damage Control
DCFF	Damage Control and Firefighting
DLS	Decoy Launching System
DRC	Design Research Centre
Dstl	Defence Science and Technology Laboratory (UK Ministry of Defence)
EPSRC	UK Engineering and Physical Sciences Research Council
FOC	First of Class
FP	Fire Pump
FPP	Fixed Pitch Propeller
FRP	Fire and Repair Party
FRPP	Fire and Repair Party Post
GRC	Graphics Research Corporation Limited
GT	Gas Turbine
HPAC	High Pressure Air Compressor
HTS	High-temperature Superconducting
IR	Infra-red
LCS	Littoral Combat Ship
MOD	Ministry of Defence
NBCD	Nuclear, Biological and Chemical Defence

NES	Naval Engineering Standards
PM	Performance Measure
RCS	Radar Cross Section
SAM	Surface-to-air Missile
SCC	Ship Control Centre
SURFCON	Surface Ship Concept module in GRC Paramarine
SURVIVE	Surface and Underwater Ship Visual Vulnerability Evaluation tool
TLC	Through Life Cost
UPC	Unit Production Cost
VLS	Vertical Launching System
WT	Watertight
WTD	Watertight Door

1. INTRODUCTION

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' [1], where in the current case the 'weapon system' signifies a naval ship. Survivability is generally considered to encompass three constituents, susceptibility, vulnerability and recoverability. Susceptibility is related to a ship being detected, identified, targeted and hit; vulnerability refers to the damage caused by an incident; while recoverability is concerned with the extent to which capability can be recovered and the time needed to recover. Each of the three constituents is highly dependent (amongst other factors) on the ship configuration, which in turn is produced during the crucial early ship design stages. However, the driving issues in preliminary ship design, alongside accommodating the combat system, have traditionally been powering, stability, strength and seakeeping. Therefore, survivability related issues have only been investigated during the later detailed design stages and heavily constrained by the major design features being fixed by then. In addition, the lack of an integrated survivability assessment and quantification method, which can be utilised during the early design stages, when combined with rising warship procurement costs can lead to cost cutting in this complex and critical topic, resulting in ship designs with inappropriate levels of survivability.

The objective of the study described in this paper is to develop an integrated survivability assessment approach and demonstrate it on a range of ship types and hullform configurations. The ship designs used throughout the study are at a preliminary level of design detail. The principal drivers for survivability and their cost-effective incorporation in ship design have been investigated. In addition the paper presents the advantages of using an architecturally orientated preliminary ship design approach in conjunction with the proposed survivability assessment method. Such preliminary design approaches can bring survivability performance issues into appropriate consideration in the earliest design stages.

The above work is being carried out in the UCL DRC, which was established in 2000 as part of the Marine Research Group of UCL [2]. This CAD focused group makes use of the QinetiQ GRC's [3] Paramarine Preliminary Ship Design Software with the incorporation of the UCL developed Design Building Block approach, in order to innovatively investigate preliminary design [4].

2. BACKGROUND

2.1 THE DESIGN BUILDING BLOCK APPROACH

Traditionally, naval architects have focused on the areas of speed, seakeeping, stability and strength as the driving issues in preliminary ship design. In contrast, 'style' related issues were examined at later stages [5], despite the fact that warships are generally not weight or space limited, but architecturally driven [6].

Andrews' [7] proposal to integrate ship architecture with the traditional numerical techniques was followed by the demonstration of 'creative synthesis' [5] which was presented in a paper entitled 'An Integrated Approach to Ship Synthesis' [8]. From this work, a new methodology, namely the DBB approach [9] was developed.

The basic idea behind the DBB approach is for the designer to separate the ship's functions and sub-functions into discrete elements (Design Building Blocks) and position them appropriately, putting architectural factors in the centre of the process, in contrast to the traditional sequential design process [9]. This method allows a more thorough exploration of alternative designs to meet the particular requirement, as well as encouraging novel solutions [9] [10]. A summary of the DBB approach is given in Figure 5 of [9] reproduced below.

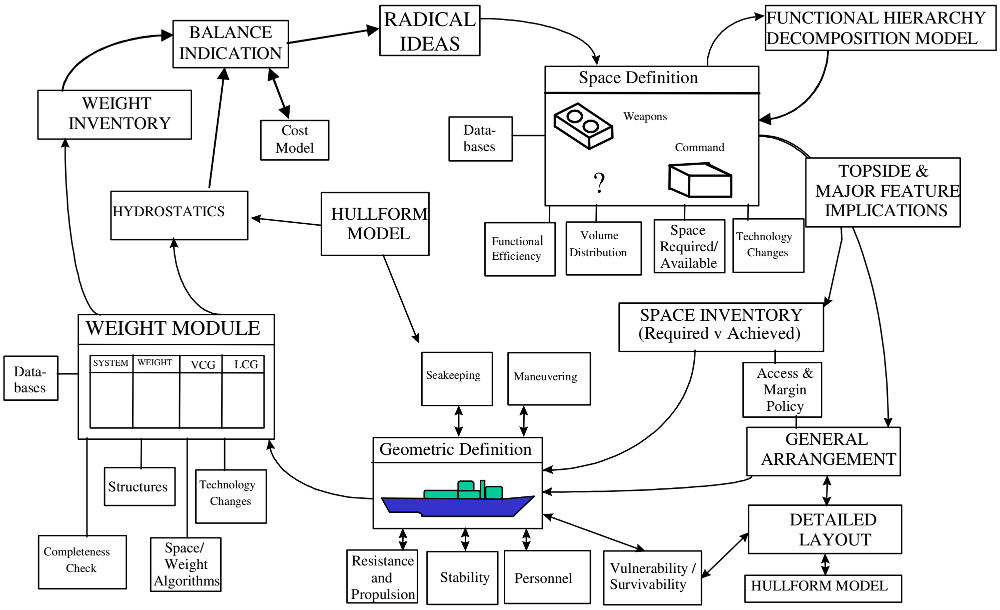

Figure 1: Building Block Design Methodology Applied to Surface Ships [9]

The above approach to preliminary ship design was developed and implemented following the rapid developments in computer capability through QinetiQ GRC's SURFCON implementation [11], described in [12]. By implementing the DBB approach through the SURFCON module in Paramarine, the DBB approach is linked to an already commercially established preliminary ship design module [11]. This way, SURFCON can draw on all the naval architectural analytical tools (stability, powering seakeeping, vulnerability, manoeuvring, structural analysis, etc.) available in Paramarine [12]. Consequently, a fully integrated preliminary design process, architecturally centred and combined with traditional naval architectural numerical analysis techniques to achieve balance [13] is possible through SURFCON and has been shown to be applicable to a wide range of conventional and unconventional ships [4].

2.2 SURVIVABILITY

The NATO definition of survivability is summarised in Figure 1.2-1 of [1] which is reproduced below.

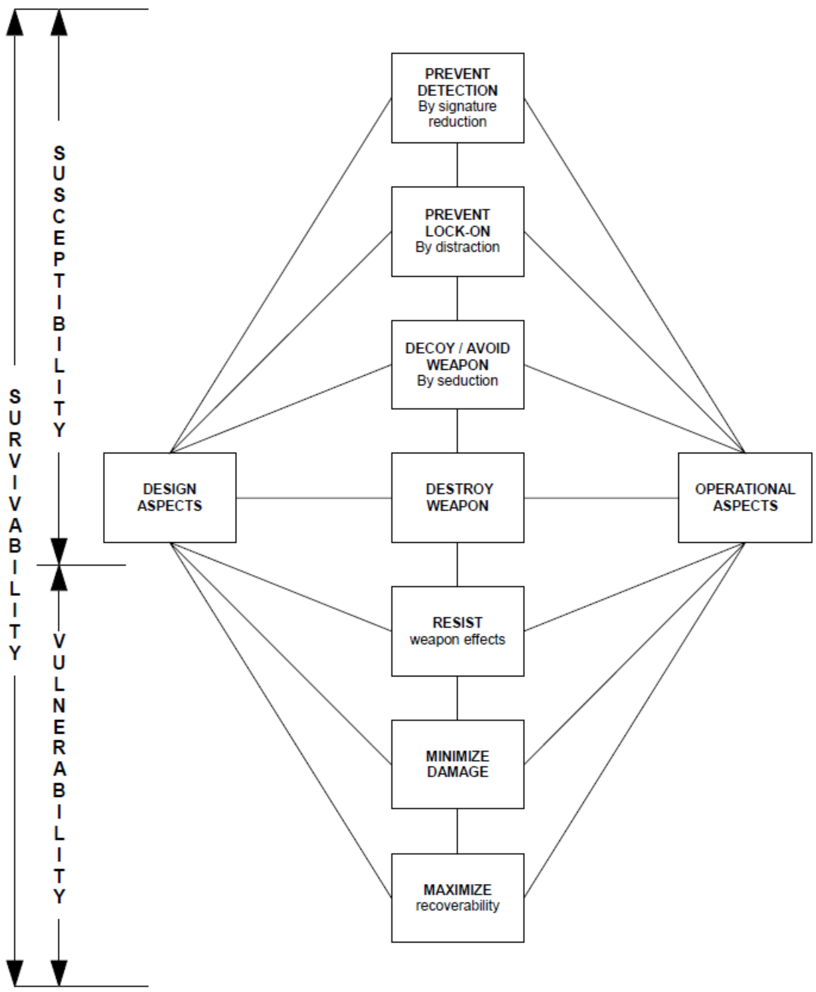

Figure 2: Survivability is a Subject, Which Depends on the Interrelation of Many Subjects. Not Only Design but Also Operational Effects Can play an Important Role in Ship Survivability [1]

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 much harsher conditions than those normally imposed by the marine environment [14] [15]. In order to survive such conditions, the inherent survivability due to a ship's construction needs to be complemented by additional survivability features [15]. These requirements (such as signature management and robust structural design) constitute the main distinctions between commercial and naval ship design [14] [16]. Such requirements not only increase the complexity of naval ships [14] but are also difficult to quantify [17].

Modern warships are often criticised for their survivability performance for a number of reasons. For example, the lack of armoured protection on modern combatants and the increase in complicated and sensitive sensors and electronic equipment (shift from enhanced armour to sensor capability), the increasing diversity of threats faced by such ships (improvements in weapons technology and shift towards littoral operations), the reduced manning levels [18], the declining defence budgets leading to smaller fleets [19] and the adoption of commercial standards and equipment in warships [20] [21]. The above have justified the need for a new naval ship design philosophy aiming at a more coherent approach to warship survivability [18].

Prior to recent performance based specification with respect to survivability, ship requirements were often vague in this regard. The difficulties in quantifying survivability can therefore mean that survivability features are hard to justify, and hence they can often be seen to be an attractive area for cost cutting [22] [23]. This could however lead to 'unstable areas where there is no viable design' [6]. Thornton et al [24] have also criticised the way in which survivability is costed and incorporated in naval vessels. They suggests that in many cases (e.g.: shock protection) it is the existence of a laid down level of survivability and not the level of protection required that has led to the increase in cost, affecting particularly the FOC. Aspects in the ship capability, such as defensive weapons and electronic warfare, TLC and manning are usually not taken into account in costing survivability [24]. Martin [25] argues that many survivability features address more than one capability, and therefore assessing their impact on the cost of survivability is difficult. Also, survivability features, such as reducing radar susceptible microgeometry by placing equipment behind bulwarks or below deck, leads to cost benefits by better protecting the equipment and facilitate easier maintenance [24] [26]. In addition, it has been argued that, as is the case with most design features, survivability features are easier to incorporate if they are considered and implemented at the earliest design stages. If they are left until later stages they are not only more likely to be expensive, but may well be impossible to incorporate [19] [22].

It is increasingly acknowledged that the required survivability level should be specified during the development of the operational requirements. The survivability requirements should be set in terms of meeting specific threats and achieving specific outcomes defined by the customer, drawing on validated analysis tools [23] [27]. This then makes survivability an integral part of the design process [28] and can therefore assist in achieving a balance between the three survivability components and also with other design features [29] with consideration to their associated weight, volume and cost implications [30].

2.3 CONCLUSIONS ON THE NEED FOR SURVIVABILITY

The rising cost of warship procurement, coupled with declining defence budgets, has led to a reduction in the number of ships in most western navies. These developments can be ameliorated through innovation in the ship design process and in individual ships. Innovation has to be addressed in the early design stages, where the design resources expended are relatively minimal but most major decisions are taken. Recent progress in computer technology can be utilised to realise such innovations. Since most modern warships are architecturally constrained, architecturally orientated preliminary design methods are best employed to address such issues.

Cost cutting is often focused on aspects which are difficult to quantify, such as survivability. This can lead to unfeasible designs given the increased complexity of modern naval operations, often focused in littoral waters, where a wide range of threats is likely. A number of survivability assessment tools currently exist, however, most are either aimed at a single survivability constituent, being unable to balance between survivability reduction features; and/or are qualitative, therefore inadequate for quantifying requirement specification; and/or are aimed towards detailed designs, where implementing substantial changes is impractical or prohibitively expensive.

Therefore, there is a need for a simple and rapid method to fully integrate and quantify naval ship survivability. Since survivability is layout sensitive, such a method should take advantage of architecturally orientated ship design processes, integrating survivability into the early iterative design process. In being applied to early stage design, given there is minimum detail, survivability features become amenable to change. The proposed method combines a number of tools used by UCL and the UK MOD, as well as a new approach quantifying recoverability. In particular this approach overcomes the difficulties of modelling recoverability (i.e. lack of data, human performance and time dependence) by using weighted performance measures.

3. PROPOSED APPROACH

3.1 SUSCEPTIBILITY

For the approach to be valid, it should work for a range of scenarios. However, in order to demonstrate the approach, it was decided that a single threat scenario should be developed. The scenario selected was that of a ship being attacked by radar homing ASMs (at 15GHz). Three probabilities were calculated for the susceptibility part of the approach. The probability of the ship being detected and identified, *P(di)* (assumed to be equal to 1), the probability that the missile locks on the ship, *P(l)*, and the probability of the ship being hit by at least one ASM *P(h)*.

In order to calculate *P(l)*, it was decided to utilise the SPECTRE software (the current UK MOD RCS prediction tool [25] [31]). The ship designs to which the method was applied were given to the sponsor of this research (Dstl) who ran them on SPECTRE in order to obtain RCS results. Given that if the decoy's RCS is equal to that of the ship, there is a 50% chance of the ASM locking onto the ship [18], *P(l)* values were obtained by assuming a linear relationship. The chaff RCS was assumed to be 2,000m2 between 10-20GHz, although even higher values were given in reference [32] and in [33] [34]. The average ship RCS, around 360o, at an elevation of 0o and frequency of 15GHz was used in the *P(l)* equation.

P(h) was then calculated through the UCL developed CSEE [35]. The CSEE, developed by UCL as part of its MSc in Naval Architecture course, was used to estimate defensive system effectiveness [35]. The CSEE is able to calculate probabilities of layered defence success against missile attack scenarios; however it is relatively simple and relies on various assumptions. Unclassified but representative weapons data (such as range, maximum burst time for CIWS, firing rates, reaction times, kill assessment times, velocities and single shot kill probabilities) are specified to determine reaction times and success probabilities [35].

It is important to note that the factors affecting the lengthwise hit probability on a ship are not limited to ship and threat characteristics but include environmental conditions, ship motions and manoeuvring and variations in weapon performance [36]. Therefore, using RCS prediction software to obtain lengthwise hit probabilities is questionable [36]. Consequently, example hit grid probabilities were generated using a manual method of assessing the ship's geometry. In future, this could be replaced with a more sophisticated analysis.

3.2 VULNERABILITY

For the vulnerability element of the method, it was decided to utilise SURVIVE Lite, which is the current UK MOD vulnerability assessment tool for concept stage designs [31] [37]. It was decided that a limited amount of major ship systems should be initially modelled. Specifically only the Move system and the major Fight systems of the ships to be investigated would be modelled. It was decided that the method would first be tested on frigate type ships since they are the most common type of warship for most navies with blue water aspirations [4]. Therefore, the major fight systems modelled were:-

- Medium calibre naval gun system;
- ASM system;
- Aft SAM system;
- Forward SAM system;
- Helicopter system.

In preliminary design only major system components are considered, while items such as cables and pipes connecting system components are neglected [38] and SURVIVE Lite is capable of operating at this level of definition.

It was also decided that hit grids (**Figure 3**) should be separately applied to each WT section (for both port and starboard sides) of each ship and vulnerability results for each modelled system obtained. These results were then multiplied by the probability that the given WT section was hit and then this was summed in order to obtain the total system vulnerability for each system.

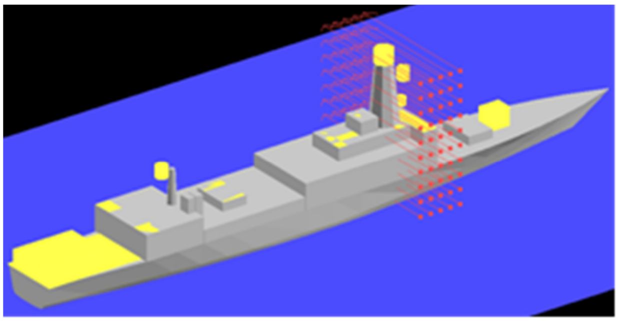

Figure 3: SURVIVE Lite Hit Grid (Frigate Variant 1, port side attack)

A weighting scheme was applied to the modelled systems as advised by Portuguese Navy officer, 1st Lt. Pedro Fonseca who had been a frigate damage control officer in his recent seagoing appointment. The weighting scheme is in accordance with the warship objective hierarchy 'to float, to move, to fight' [39] and is shown in **Table 1**.

Table 1: System Weighting Scheme Adopted

MOVE	Move	9	= 9
FIGHT	Gun	2	
	ASM	2	
	Aft SAM	1	
	Fwd SAM	1	
	Helicopter	2	= 8

The final vulnerability results were obtained by applying the above weightings, taking the sum of individual system vulnerabilities and normalising with respect to a baseline frigate design.

In addition to the Move system and major Fight systems and their components, the following items were modelled in SURVIVE Lite:

- ATU and ventilation compartments;
- Firepumps;
- NBCD stores;
- FRP section bases;
- Workshops;
- Naval stores;
- Spare gear stores.

These items were modelled in order to obtain vulnerability values of components necessary for recoverability, so these could be used in the recoverability section of the approach (see Section 3.3).

Finally, the fast fire algorithm of SURVIVE Lite [40], which is relevant to preliminary stage ship design, was employed in order to determine further system and component damage due to secondary weapon effects. It is to be noted that damage due to flooding was not considered since only abovewater threats were addressed in the example.

3.3 RECOVERABILITY

Modelling recoverability is the most demanding area of survivability assessment. This is due to a number of reasons, such as the limited ability to model secondary damage and crew actions, the inadequate data available and the difficulty of incorporating crew readiness and skill levels. It was decided that simulations were not practical for the level of ship definition in these ship design studies. However, assessment of recoverability requires temporal metrics such as the time taken to repair systems, which would be produced by simulation. An alternative analytical method is thus required to generate this data. Moreover methods, such as safety and risk analysis, are not quantifiable but rather are subjective since they usually rely on expert judgment and, furthermore, do not take specific ship architectural features into account and so are considered to be of limited use. It was therefore concluded that a new recoverability assessment method should be developed. This works on the basis of developing a number of Performance Measures (PMs) and an appropriate weighting scheme in order to attempt to overcome limitations such as the ones listed. PMs were taken from existing safety and risk ranking methods as well as new ones being developed. Values for those PMs were obtained using the software employed, i.e.: Paramarine and SURVIVE Lite.

The PMs developed were split into three categories. Again, the weighting schemes of all PMs were derived with the assistance of 1st Lt. Pedro Fonseca, Portuguese Navy. Note that the larger the value of a specific PM is, the worst its performance. The first category which is detailed in **Table 2** consists of PMs related to immediate effects on DCFF.

Table 2: Immediate DCFF Performance Measures (Category 1)

PM	Software	Weighting
Average distance between FRPP and damaged compartment centre (m)	Paramarine	7
Average number of WTD operated per FRP	Paramarine	4
Number of internal decks in damaged compartment	Paramarine	6
Average total width of alternative routes (inverse) (m)	Paramarine	7
ATU and Ventilation (of damaged zone) (man-hours)	SURVIVE Lite	8
Fire pump (of damaged zone) (man-hours)	SURVIVE Lite	2
Overall fire pump system (man-hours/no of equipment)	SURVIVE Lite	8
NBCD stores - aft FRP section base	SURVIVE Lite	1
NBCD stores - fwd FRP section base	SURVIVE Lite	1
Remaining NBCD stores	SURVIVE Lite	2
Power (of damaged zone) (man-hours)	SURVIVE Lite	2
Overall power system (man-hours/no of equipment)	SURVIVE Lite	8
SCC (HQ1) (man-hours)	SURVIVE Lite	6
Bridge (man-hours)	SURVIVE Lite	2
Ops. Room (man-hours)	SURVIVE Lite	6
Aft FRPP	SURVIVE Lite	10
Fwd FRPP	SURVIVE Lite	10

Note that since the above PMs relate to the immediate actions/effects of an ASM hit, secondary damage effects (i.e. fire damage in this case) are not accounted for.

Category 2 of PMs is given in **Table 3** and relates to the items necessary for major system recovery, once secondary effects have been dealt with. Thus, in this case, fire effects are included by assuming a small fast fire [40] affecting all equipment items located in the hit WT section.

Table 3: Major System Recovery Performance Measures (Category 2)

PM	Software	Weighting
Aft workshops (man-hours)	SURVIVE Lite	3
Fwd workshops (man-hours)	SURVIVE Lite	3
Naval stores	SURVIVE Lite	1
Aft spare gear stores	SURVIVE Lite	7
Fwd spare gear stores	SURVIVE Lite	7
SCC (updated value) (man-hours)	SURVIVE Lite	6
Ops. Room (updated value) (man-hours)	SURVIVE Lite	7

It should be noted that the last two PMs in **Table 3** are updated values in comparison to those of **Table 2**, as secondary effects are added.

Category 3 of PMs is given in **Table 4** and includes PMs relevant to the recovery of the specific major systems selected and was applied to all these systems. Fire damage effects were included in a manner similar to Category 2.

Table 4: Individual Major System Recovery Performance Measures (Category 3)

PM	**Software**	**Weighting**
Minimum man-hours for system to be functioning	SURVIVE Lite	10
Number of man hours for system to be 100%	SURVIVE Lite	3
Access measure from naval stores	SURVIVE Lite and Paramarine	1
Access measure from aft spare gear stores	SURVIVE Lite and Paramarine	3
Access measure from aft workshops	SURVIVE Lite and Paramarine	2
Access measure from fwd spare gear stores	SURVIVE Lite and Paramarine	3
Access measure from fwd workshop	SURVIVE Lite and Paramarine	2
Equipment in damaged section measure	SURVIVE Lite and Paramarine	8

The above access measures are then quantified by multiplying the Criticality (see below) of selected equipment items by the number of man-hours needed to repair that equipment item when affected by the hit. These PMs were only applied to equipment requiring personnel to cross the damaged WT section to get access from the corresponding store/workshop. Criticality is given by 1/(number of equipment items in parallel). For example, if there are two propellers in the ship, both providing the same service, each has a Criticality of ½. The last PM in **Table 3** was obtained by multiplying the Criticality by the number of man-hours needed to repair each equipment item which was affected by the given hit and was located in the damaged WT section in question.

All PMs obtained that have the indication SURVIVE Lite, under the Software category in **Tables 2**, **3** and **4** (with the exceptions of stores and personnel) were measured in man-hours to repair that system/component. Man-hour data for the repair of various equipment categories were provided by the sponsor (Dstl) and were the same values as has been employed by SURVIVE in its recently developed recoverability module. Humans and stores on the other hand are assumed to be 'unrecoverable'; i.e.: the associated PMs were given a value of 0 if they survived and 1 if killed. It is to be noted that for the recoverability section of the approach, it had to be assumed that the ships investigated would be 'successfully' hit (i.e. the probabilities of susceptibility and vulnerability had to be equal to 1), therefore SURVIVE Lite was just used to indicate which equipment items were affected by the hit without invoking specific values for vulnerability.

As mentioned in Section 3.2, SURVIVE Lite was run separately for each WT section of each ship design. Therefore, values for the PMs were obtained for each WT section. The sum of each PM had to be taken over the entire ship and normalised with respect to the baseline ship, given the weightings shown. The sum of each PM category was then taken and again normalised with respect to the baseline, given the weightings shown below. As in **Table 1**, the weightings chosen for each PM category were in accordance with the warship objective hierarchy 'to float, to move, to fight' [39] and are shown in **Table 5**.

Table 5: Recoverability Weighting Scheme

<table>
<tr><td>Category 1 PMs</td><td>FLOAT</td><td colspan="2">10</td><td>= 10</td></tr>
<tr><td>Category 2 PMs</td><td>Recovery support</td><td colspan="2">2</td><td></td></tr>
<tr><td rowspan="6">Category 3 PMs</td><td>MOVE</td><td>Move</td><td>9</td><td>= 9</td></tr>
<tr><td rowspan="5">FIGHT</td><td>Gun</td><td>2</td><td rowspan="5">= 8</td></tr>
<tr><td>ASM</td><td>2</td></tr>
<tr><td>Aft SAM</td><td>1</td></tr>
<tr><td>Fwd SAM</td><td>1</td></tr>
<tr><td>Helicopter</td><td>2</td></tr>
</table>

The above procedure of populating the PM matrices for each ship design is briefly summarised in **Table 6**, without specific numerical values.

Table 6: Scheme for Compiling the Performance Measures Matrix

			WT Section	**A**	**B**	**C**	**…**							
			Weigh-ting					**Sum**	**Norm w.r.t. baseline**	**Weigh-ted**	**Group Sum**	**Norm w.r.t. baseline**	**Weigh-ted**
	Cat. 1 PMs	$PM_{1.1}$											
		$PM_{1.2}$											
		$PM_{1....}$											
	Cat. 2 PMs	$PM_{2.1}$											
		$PM_{2.2}$											
		$PM_{2....}$											
Move	Cat. 3 PMs	$PM_{3.1.1}$											
		$PM_{3.1.2}$											
		$PM_{3.1....}$											
Gun	Cat. 3 PMs	$PM_{3.2.1}$											
		$PM_{3.2.2}$											
		$PM_{3.2....}$											
ASM	Cat. 3 PMs	$PM_{3.3.1}$											
		$PM_{3.3.2}$											
		$PM_{3.3....}$											
Aft SAM	Cat. 3 PMs	$PM_{3.4.1}$											
		$PM_{3.4.2}$											
		$PM_{3.4....}$											
Fwd SAM	Cat. 3 PMs	$PM_{3.5.1}$											
		$PM_{3.5.2}$											
		$PM_{3.5....}$											
Helo	Cat. 3 PMs	$PM_{3.6.1}$											
		$PM_{3.6.2}$											
		$PM_{3.6....}$											
												Total Score		

The final step in the procedure is to normalise the total score of each ship with respect to the baseline design.

3.4 TOTAL SURVIVABILITY

In order to come up with a total survivability output, the results from the above procedures had to be combined. It was decided that PM matrices, identical to that shown in **Table 6** would be used for total survivability. However, now the percentage values of susceptibility of each WT section and vulnerability of each equipment item / system had to be multiplied with each PM. Therefore, unlike the approach adopted in Section 3.3, susceptibility and vulnerability were not assumed to be equal to 1. More specifically, all PMs derived from the Paramarine model were multiplied by susceptibility values obtained from the corresponding WT section. For the remaining PMs (again with the exception of stores and personnel), the number of man-hours to repair a specific item were multiplied by both the susceptibility of the hit WT section and the vulnerability of the item, given a hit in that section. Personnel and stores again were assumed to be 'unrecoverable'.

An alternative way of presenting total survivability results that avoids the need to multiply susceptibility, vulnerability and recoverability scores together is to adopt star plots. This approach drew on the work of Vasudevan [41] and its advantages are discussed in Section 4.2.

4. APPLICATION AND RESULTS

4.1 APPLICATION

As previously noted, it was decided that the survivability assessment method should be validated for frigate type ships. All ship studies designed in this investigation were designed in accordance with the latest procedures, using the DBB approach through its SURFCON implementation in Paramarine. The studies were designed and sized according to the procedures and data available for the ship design projects of the MSc in Naval Architecture at UCL [42] [43] with additional sources readily available. In addition all the ship studies were designed with the clear objective of maximising survivability, based on good practice.

Initially, three general ocean going sea control frigates were designed, all of which were fitted with an identical weapon fit:-

- 1 x BAE Systems 155mm gun
- 2 x MSI Seahawk 30mm
- 2 x 4 Harpoon launchers
- 4 x MBDA MICA PDMS with 32 MICA missiles (4 x 8 round VL launchers)
- 1 x Lynx (Kestrel) Helicopter + hangar and single spot flight deck for EH-101 Merlin
- 2 x Triple barrel torpedo tubes
- 4 x Rheinmetall MASS Decoy Launchers
- 1 x Surface Ship Torpedo Defence System
- 2 x Navigation radars
- 1 x Single Face SR STAR Surveillance Radar
- 1 x General Purpose Electro Optical Device
- 2 x Thales Sirius IRST
- 1 x Raytheon AN/SLQ-32(V)3 Shipboard ESM/ ECM System
- 1 x Spherion hull mounted sonar
- 1 x Small ship communications system (1 x comms. mast + 2 x whip antennae)
- 1 x Generic Satellite Communications System with 2 antennae
- 25 embarked forces.

In addition, all three frigates had the same performance requirements, listed in **Table 7**, and their complements were sized based on current combatants' complement / displacement densities.

Table 7: Frigate Performance Requirements Adopted for Design Studies

Max. speed:	30kts
Endurance:	7,000nm at 15kts
Stores:	30 days
Damage stability:	Defence Standard 02-109 (NES 109) damage criteria assessment [44]
Zoning:	Four zones with maximum independence.

The baseline frigate, Variant 1, (**Figure 4**) is a typical modern frigate with a one passing deck hull and a continuous superstructure out to the ship's side. There is a centreline passageway on the DC deck (No 2 Deck). The hull is based on that of the Type 22 and was generated using the Quickhull object of Paramarine and includes twelve main WT bulkheads, of which three constitute the main zone boundaries. Each of the four zones includes independent power generation units, CWP, HPAC, FP, ventilation and ATU, NBCD stores and airlocks.

Figure 4: Paramarine Overall Representation of the Frigate Variant 1 Ship Design Study

Variant 2 (**Figure 5**) adopted a deeper, two passing deck hull, minimal superstructure and a flight deck close to amidships, to explore the survivability related advantages of such configurations. It consists of two access decks (No 2 and No 3 Decks), each with a centreline passageway. Its hull was generated in the same manner as that of Variant 1 and includes the same number of bulkheads. However, because of the relatively small superstructure length it proved quite difficult to include airlocks (and NBCD) stores in all four zones, so they were only fitted in three zones.

Figure 5: Paramarine Overall Representation of the Frigate Variant 2 Ship Design Study

For the final variant, Variant 3 (**Figure 6**), a trimaran configuration was selected to investigate the possible advantages of this unconventional hull type. The hull was generated using a UCL developed algorithm and included thirteen main WT bulkheads, of which three were main zone boundaries. Similar to Variant 1, each zone includes independent prime movers, CWP, HPAC, FP, ventilation and ATU, NBCD stores and airlocks. Due to the narrow beam of the main hull, a fifth, non-passing, deck was included in order to incorporate the main machinery and systems. The box structure contains two side passageways on the DC deck which converge to a centreline passageway in the forward section of the hull. The superstructure is relatively minimal and was split into two structurally separate blocks, one slightly aft and one slightly forward of amidships.

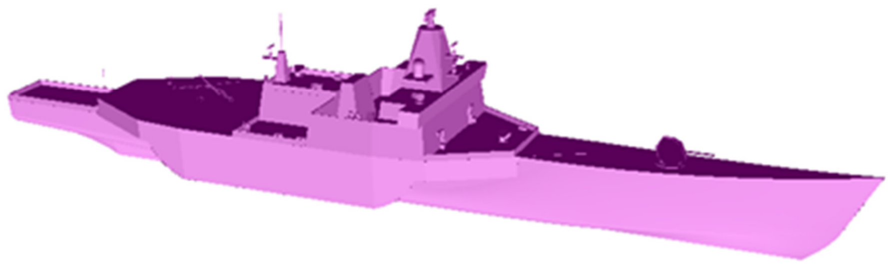

Figure 6: Paramarine Overall Representation of the Frigate Variant 3 Ship Design Study

Principal particulars of the three frigate variants are listed in **Table 8**.

Table 8: Principal Particulars of Frigate Variants Investigated

Variant 1	
Dimensions:	132.2m x 16.1m x 9.7m (deep draught 4.0m)
Displacement:	3,880te deep, 3,280te light
Maximum Speed:	30kts
Range:	7,000nm at 15kts, 6,000nm at 18kts
Power Plant:	1 x 31MW GT (boost), 2 x 2.94MW diesels (cruise), 2 x 2.69MW diesels (auxiliary) driving two FPPs on 20MW HTS motors
Accommodation:	11 officers, 137 ratings, 25 embarked forces
Variant 2	
Dimensions:	125.2m x 16.1m x 12.1m (deep draught 4.4m)
Displacement:	4,020te deep, 3,440te light
Maximum Speed:	30kts
Range:	7,000nm at 15kts, 5,900nm at 18kts
Power Plant:	1 x 31MW GT (boost), 2 x 5.22MW diesels (cruise), 2 x 2.69MW diesels (auxiliary) driving two FPPs on 21MW HTS motors
Accommodation:	11 officers, 141 ratings, 25 embarked forces
Variant 3	
Dimensions:	150.3m x 29.2m x 12.4m (deep draught 5.2m)
Displacement:	4,320te deep, 3,840te light
Maximum Speed:	31kts
Range:	7,000nm at 15kts, 5,900nm at 18kts
Power Plant:	1 x 31MW GT (boost), 2 x 2.94MW diesels (cruise), 2 x 2.69MW diesels (auxiliary) driving one FPP on a 37MW HTS motor and one pump jet on a 3.5MW motor
Accommodation:	12 officers, 152 ratings, 25 embarked forces

4.2 RESULTS

As previously noted, RCS data was obtained from SPECTRE. The UCL CSEE was applied to the three ship design studies with four ASMs being fired against each ship. The output showed that the frigates had enough time to fire seven defensive missiles against the incoming threats. **Table 9** presents the susceptibility results for the three frigates, while **Figure 7** illustrates susceptibility normalised with respect to the baseline. Note that *P(h)* was equal for all three ships due to them being fitted with identical defensive systems.

Table 9: Susceptibility Results for the Three Frigate Design Studies

	Frigate Variant 1	Frigate Variant 2	Frigate Variant 3
Average RCS (m2)	2671.7	1045.9	928.8
P(di) (%)	100.0	100.0	100
P(l) (%)	66.8	26.2	23.2
P(h) (%)	32.6	32.6	32.6
***P(susc.)* (%)**	**21.8**	**8.5**	**7.6**

As previously mentioned a simple lengthwise probability hit distribution based on ship geometry, was used to calculate the probability that each WT section would be hit. System vulnerability results were then multiplied by the probability that that specific WT section was hit and the values for each system added in order to obtain the total system vulnerability (**Figure 8**).

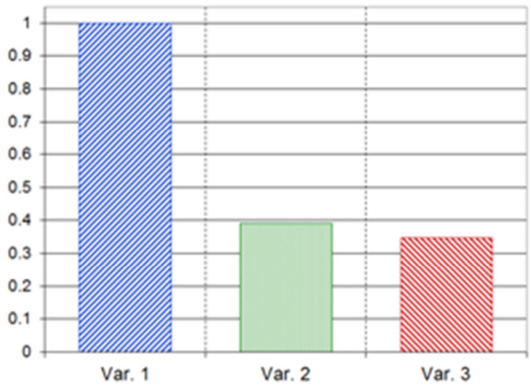

Figure 7: Normalised Plot of Susceptibility for the Three Frigate Design Variants

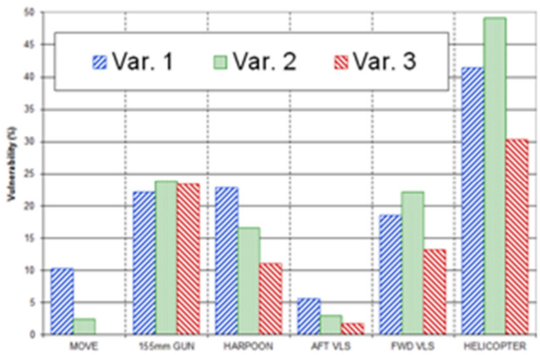

Figure 8: System Vulnerability for Six Systems for the Frigate Design Studies

The weighting scheme in **Table 1** was then applied, the sum of individual system vulnerabilities were taken and normalised with respect to Variant 1 in order to produce the results shown in **Figure 9**. Finally, recoverability for each frigate variant was assessed as described in Section 3.3. Normalised results are presented in **Figure 10**, noting that the higher the score, the worse the performance, and therefore, in effect the difficulty of recoverability in a given design is shown by the relative magnitude.

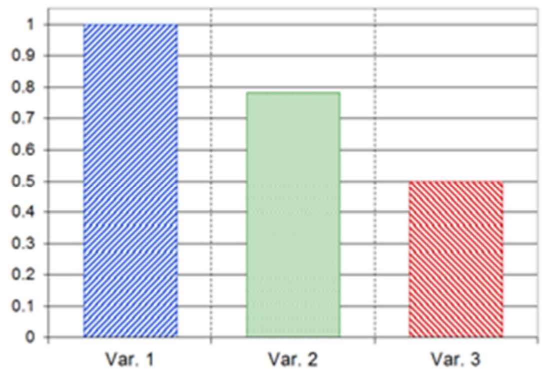

Figure 9: Normalised Plot of Overall Vulnerability for the Three Frigate Design Variants

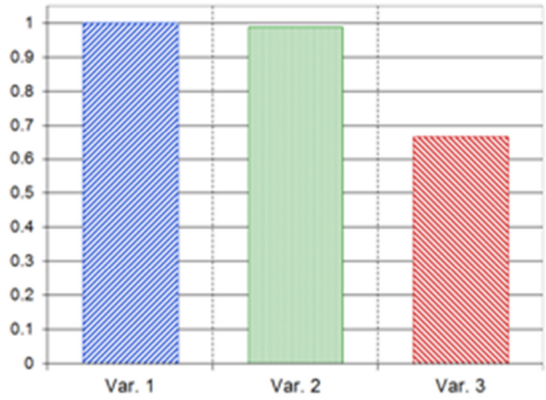

Figure 10: Normalised Plot of Difficulty of Recoverability for the Three Frigate Design Variants

After all the survivability constituent results were obtained, they were processed as described in Section 3.4 in order to obtain total survivability results (**Figure 11**). Again the higher the score, the worse the performance, consequently, difficulty of survivability is measured.

Total survivability results are also presented in the form of a star plot (**Figure 12**). This removes the need to multiply susceptibility, vulnerability and recoverability data.

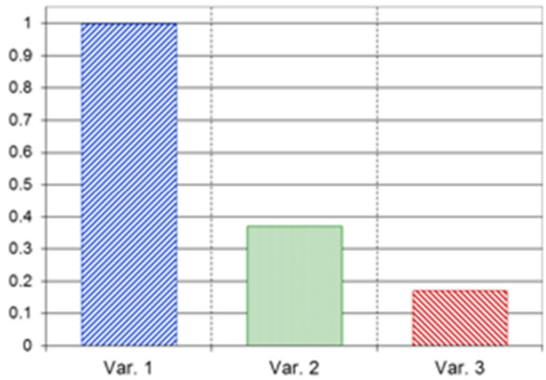

Figure 11: Normalised Plot of Difficulty of Survivability for the Three Frigate Design Variants

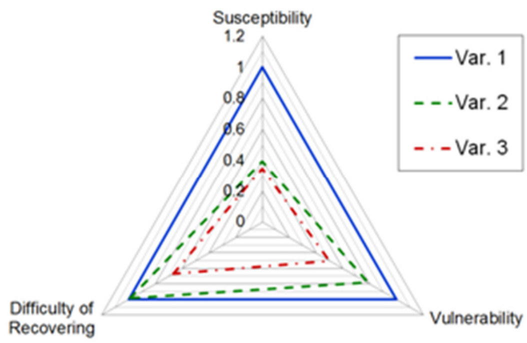

Figure 12: Normalised Star Plot of Difficulty of Survivability for the Three Frigate Design Variants

The data plotted in **Figure 12** are identical to those of **Figures 7**, **9** and **10**, and each 'star' (triangle in this case) represents a specific ship design. An advantage of this type of presentation of the results is that further spokes, such as cost, displacement and power can be added; a limitation, however, is that it can only depict characteristics that are currently amenable to quantification [41]. There is also the issue of how the diagram would be interpreted, with regards to the significance of the enclosed area. Visualisation and comparison methods are an area for further development.

5. DISCUSSION

Some general conclusions regarding the three frigate variants can be drawn. When considering susceptibility, the baseline variant performs least well. This could be attributed to the fact that it has a full length superstructure, compared to the minimal superstructures of Variant 2 and Variant 3. Frigate Variant 3 is marginally less susceptible than Variant 2. This is probably due to the fact that the DLSs on Variant 2 were not positioned behind bulwarks, therefore, resulting in a slightly higher RCS for this design.

In terms of vulnerability, once again Variant 1 has the worst performance. However, the vulnerability results are sensitive to the lengthwise hit probability distribution. Had this been linear, Variant 2 would have performed marginally below the baseline design. Either way, the trimaran frigate produces the best results by a significant margin. This can be attributed to several reasons:-

- The significantly larger size of the ship allows a better distribution of equipment and systems with wider separation between parallel items;
- The side hulls act as a protective shield to the main hull, mainly affecting equipment and compartments below the DC deck and amidships, such as engines, magazines and fuel tanks;
- Due to the large box structure and associated wide beam, inboard equipment above the DC deck is better protected;
- Having a larger draught, items deep in the hull, such as magazines and sonar equipment rooms, are less vulnerable given only abovewater threats are considered.

It is of interest to note that the move system of Variant 3 is assessed as 0% vulnerable. This is because the system included widely separated aft (propeller) and forward (pumpjet) propulsive units. This was the preferred configuration due to the fact that the narrow main hull beam made it difficult for twin shafts to be fitted, while that was the selected option for the two monohulls. A downside of the trimaran variant is that it was generally more vulnerable above the waterline well aft and forward, probably due to its very narrow main hull offering minimum protection to equipment sited there. Another interesting conclusion drawn from Variant 2 is that an amidships flight deck, even if preferred for operational reasons, is shown to have significantly increased vulnerability using this approach.

Finally regarding recoverability, Variants 1 and 2 produce matching results for all PM categories. Benefits are gained through the use of two access decks in Variant 2, but these are cancelled out by the inferior locations of the two FRP section bases, as a result of the minimal superstructure configuration. In addition, system recovery PMs are almost identical in these variants probably due to the very similar monohull equipment and system configuration. Once again, Variant 3 produces the most promising results in every PM category. System recovery related PMs perform better due to the fact that the superior trimaran architecture described above leads to less items being damaged by a given constant threat. Regarding immediate DCFF related PMs, although FRP section bases are again not very efficiently positioned and DC crews have to travel greater distances (due to the ship being longer) plus operate more WT doors to reach the affected section (due to the larger number of bulkheads present), Variant 3 still outperforms the two monohulls. This is because the performance of the remaining PMs which are related to the systems necessary for initial DCFF, such as firepumps and power, outweigh the above disadvantages.

The above investigation makes it evident that the least survivable ship design (for the particular threat considered, which is regarded the primary anti-ship weapon to be deployed [45]), is the baseline. This is the design that shares most similarities with current frigates. Conversely, the most survivable is the novel trimaran configuration, which has only recently been considered in the naval ship design domain, with only one warship design in service, the USN's Independence Class LCS [46].

6. CONCLUSIONS

6.1 GENERAL CONCLUSIONS

The rising cost of warship procurement, coupled with declining defence budgets for western navies, has led to a reduction in the number of ships in most of those navies. This has made the need for innovation in both the design process and individual ships more essential than ever, especially at the crucial early design stages. Naval ship survivability is now seen as an integral part of naval ship design and should be investigated at the onset of design in order to improve cost-effectiveness.

A simple and relatively rapid method of measuring susceptibility, vulnerability, recoverability and, hence, total survivability has been presented and demonstrated on three design variants of a general purpose frigate, including a trimaran configuration. The method is strictly comparative and as shown through linking the Paramarine CASD software to survivability assessment tools, such as SPECTRE, SURVIVE Lite and PM techniques, it is highly sensitive to ship architecture. It takes advantage of architecturally orientated ship design approaches and can be used readily in preliminary ship design with minimum ship definition, when designs are still malleable. Thus, one can compare different configurations as well as identify improvements by tracing back the poorer PM results. Therefore, when used to assist decision making, it should increase the designer's confidence. In addition, the method removes the need for complex, expensive and time consuming simulation techniques which are often of questionable value in preliminary design when design detail is lacking. Finally, the method can model a range of different attack scenarios (including IR homing ASMs and underwater threats) by simply changing the attack scenario in the CSEE and SURVIVE Lite tools and substituting a relevant tool for SPECTRE. Current disadvantages of the approach are seen to be the fact that it does not take into account multiple hits and that statistical independence between the three survivability constituents has to be assumed for **Figure 11** type presentation (whereas **Figure 12** is more open to interpretation).

6.2 ONGOING WORK

During the remainder of the EPSRC studentship project, the following work is planned to be undertaken:

- Sensitivity tests will be carried out on the method (the details of which will be decided in discussion with the sponsor);
- At least two more combatants will be designed. It is intended that one will be a smaller combatant (corvette) and another one will be a larger combatant (destroyer). The two above additional combatant design studies will be compared to the baseline frigate by applying the survivability assessment method outlined. Therefore, the way in which each survivability constituent is affected by ship size (including varying zoning) and level of combat system and ship performance capabilities (appropriate to the ship type) will be investigated;
- Two naval replenishment ship variants will also be designed, exploring different internal layouts. The two replenishment ship variants will be compared by applying the survivability assessment method. This will enable the demonstration of the method on non-combatant ships and investigation of the survivability balance of such ship types;
- Cost analysis for the three frigate variants (including UPC and TLC) will be undertaken in order to add cost to the total survivability star plot (**Figure 12**) and give an indication as to how survivability gains could be measured against ship cost.

To date, the corvette and the first replenishment ship variant designs, mentioned above, have been completed (**Figures 13** and **14**) with the survivability assessment to follow. The overall study will be reported in future publications.

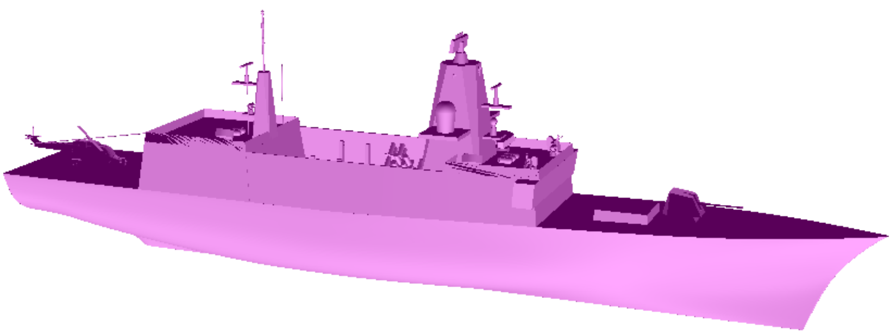

Figure 13: Paramarine Overall Representation of the Corvette Ship Design Study

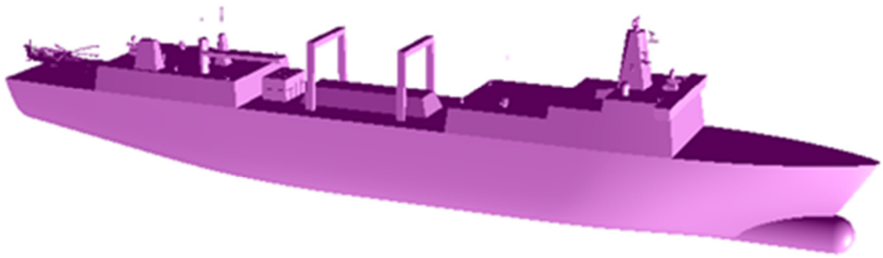

Figure 14: Paramarine Overall Representation of the Replenishment Ship Design Study

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Richard Pawling completed the MEng in Naval Architecture and Marine Engineering at University College London in 2001. He then joined the UCL DRC as a research student investigating the application of the Design Building Block approach to innovative ship design. Gaining his PhD in 2007, he has continued his research both in the DRC and via a secondment in industry. He is the recipient of the 2008 RINA Samuel Baxter Prize, 2009 RINA WHC Nicholas Prize, and 2012 COMPIT GL Award for papers describing his research.

Table A1: Vulnerability and Recoverability Categorisation of Equipment Items and Compartments Comprising the Major Ship Systems

Equipment / compartment	SURVIVE Lite (vulnerability) category	Repair (recoverability) category
Helicopter	Aircraft	Aircraft
Bridge	Control console	Light electrical × 7
ESM/ECM eq. room	Control console	Light electrical × 2
GPEOD processor	Control console	Light electrical × 2
Gun power room & store	Control console	Light electrical × 2
Gun LCR	Control console	Light electrical × 2
Harpoon LPCR	Control console	Light electrical × 2
IRST equipment space	Control console	Light electrical × 2
MFR eq. room	Control console	Light electrical × 2
Navigation radar eq. sp.	Control console	Light electrical × 2
Operations Room	Control console	Light electrical × 12
Pod drive room	Control console	Light electrical × 4
RASco	Control console	Light electrical × 5
SCC	Control console	Light electrical × 5
SeaRAM eq. room	Control console	Light electrical × 2
Sonar instrument room	Control console	Light electrical × 2
Steering gear	Control console	Light electrical × 4
Surveillance radar eq. sp.	Control console	Light electrical × 2
VLS LCR	Control console	Light electrical × 2
Auxiliary engine	Diesel generator	Heavy engineering
Cruise engine	Diesel generator	Heavy engineering
Genset	Diesel generator	Heavy engineering
Alternator	Gas turbine	Heavy engineering
Boost engine	Gas turbine	Heavy engineering
155mm gun	Gun	Light engineering
76mm gun	Gun	Light engineering
Gunbay & guntrunk	Gun	Light engineering
Weapon lift	Gun	Light engineering
Air armament workshop	Light engineering / (silo/magazine)	Light engineering
Astern refuelling	Light engineering / (silo/magazine)	Light engineering
Cargo lift	Light engineering / (silo/magazine)	Light engineering
Dry stores cargo	Light engineering / (silo/magazine)	Light engineering
Electrical maintenance workshop	Light engineering / (silo/magazine)	Light engineering
Electronic maintenance workshop	Light engineering / (silo/magazine)	Light engineering
Hangar	Light engineering / (silo/magazine)	Light engineering
Harpoon launchers	Light engineering / (silo/magazine)	Light engineering
Instrument maint. workshop	Light engineering / (silo/magazine)	Light engineering
Magazine	Light engineering / (silo/magazine)	Light engineering
Major winch block	Light engineering / (silo/magazine)	Light engineering
Mechanical maint. workshop	Light engineering / (silo/magazine)	Light engineering
Ordnance cargo	Light engineering / (silo/magazine)	Light engineering
RAS post	Light engineering / (silo/magazine)	Light engineering
SeaRAM	Light engineering / (silo/magazine)	Light engineering
VLS	Light engineering / (silo/magazine)	Light engineering
Propeller motor	Prop motor	Heavy engineering
Pumpjet motor	Prop motor	Heavy engineering
AVCAT pump	Pump	Large Pumps
Dieso pump	Pump	Large Pumps

Pumpjet	Pump	Large Pumps
ESM/ECM	Radar	Radar aerials
GPEOD	Radar	Radar aerials
IRST	Radar	Radar aerials
MFR	Radar	Radar aerials
Navigation radar	Radar	Radar aerials
Sonar	Radar	Radar aerials
Sonobuoy store	Radar	Radar aerials
Surveillance radar	Radar	Radar aerials
Flight deck	Rudder / propeller	Light engineering
Pod	Rudder / propeller	Rudder/propeller
Propeller	Rudder / propeller	Rudder/propeller
Rudder	Rudder / propeller	Rudder/propeller
Propeller shaft	Shaft	Rudder/propeller
AVCAT tank	Tank	Fluid tanks
AVCAT cargo	Tank	Fluid tanks
Dieso cargo	Tank	Fluid tanks
Intake/exhaust	Uptake / down takes	Intake/exhaust

A7.1 Combatant System Tree Diagrams

Move System

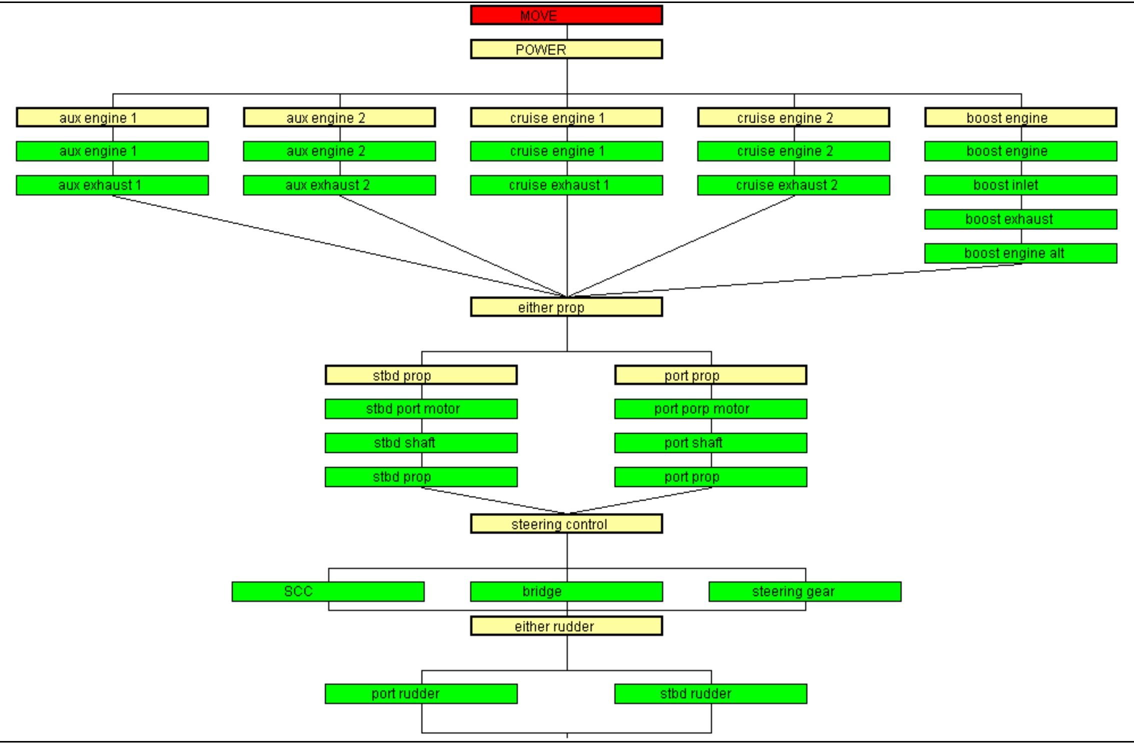


Figure A46: Frigate Variants 1 and 2 and Destroyer Move System Tree Diagram

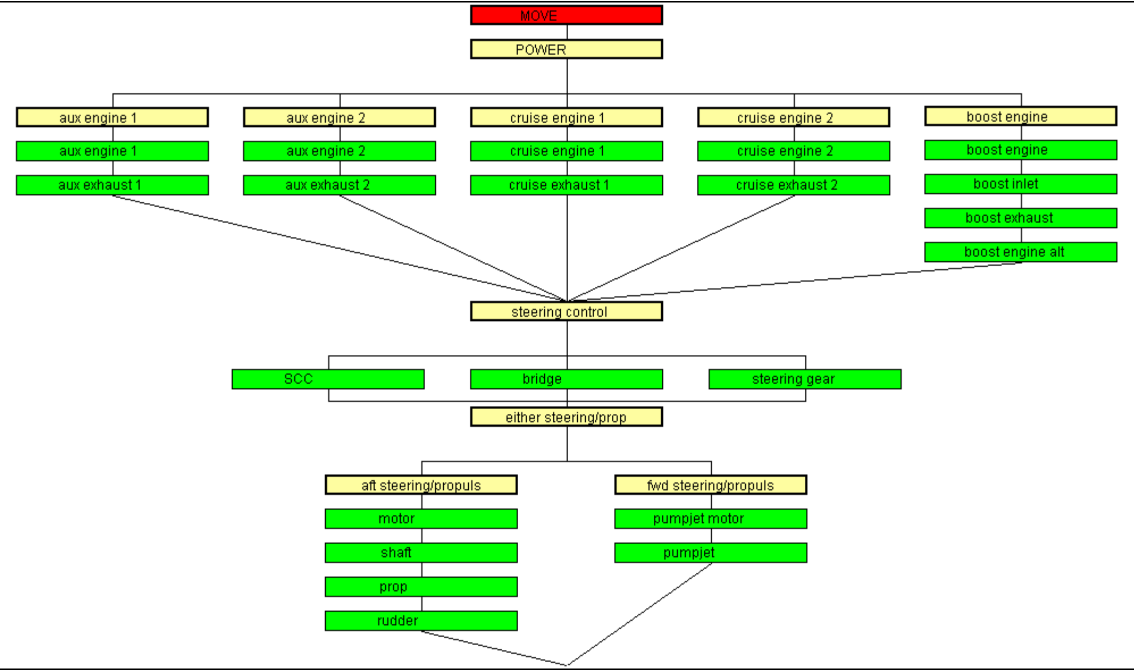


Figure A47: Frigate Variant 3 and Corvette Move System Tree Diagram Tree Diagram

Medium Calibre Naval Gun System

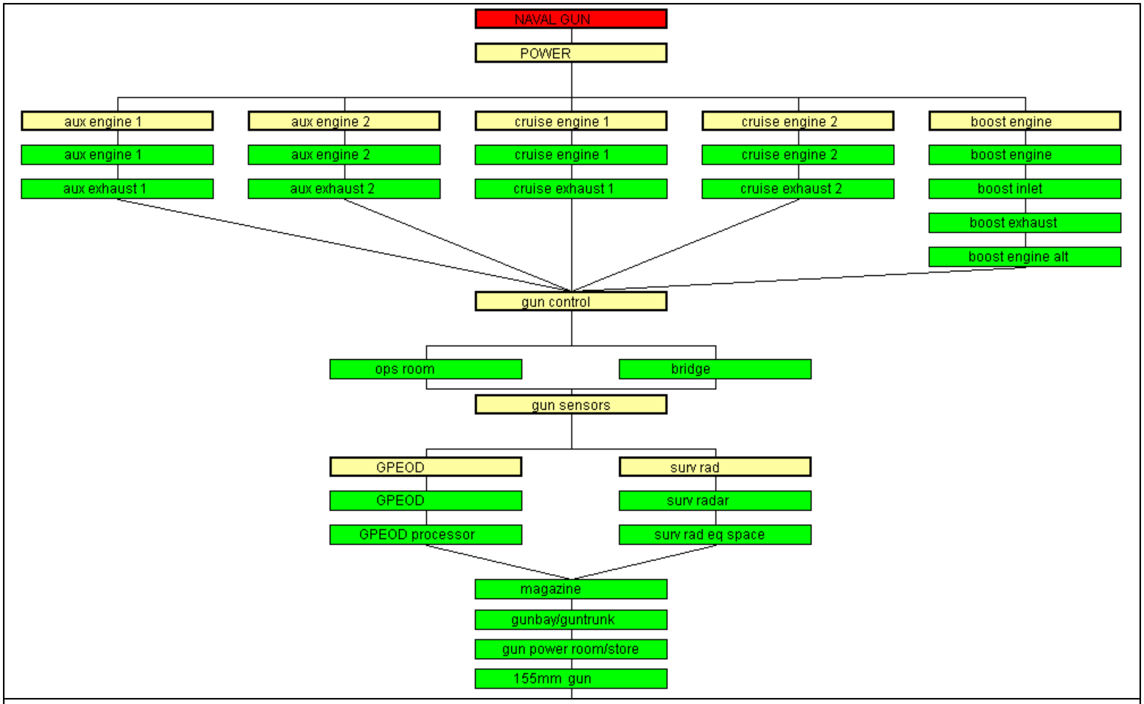


Figure A48: Frigate Variants 1, 2 and 3 Medium Calibre Naval Gun System Tree Diagram

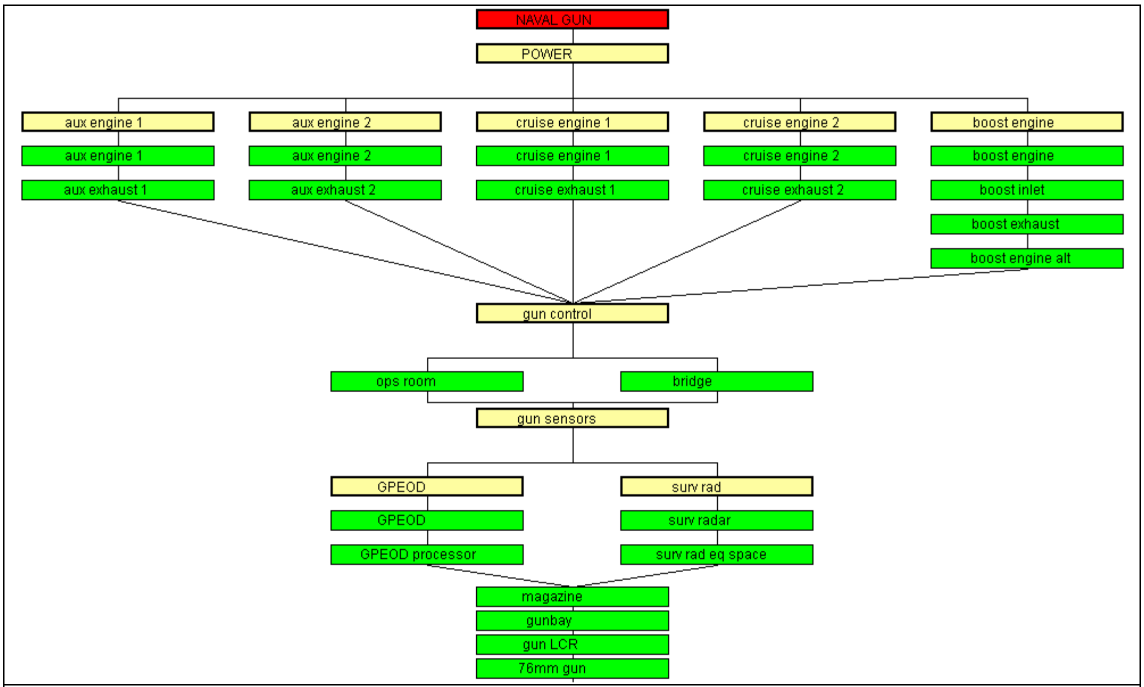


Figure A49: Corvette Medium Calibre Naval Gun System Tree Diagram

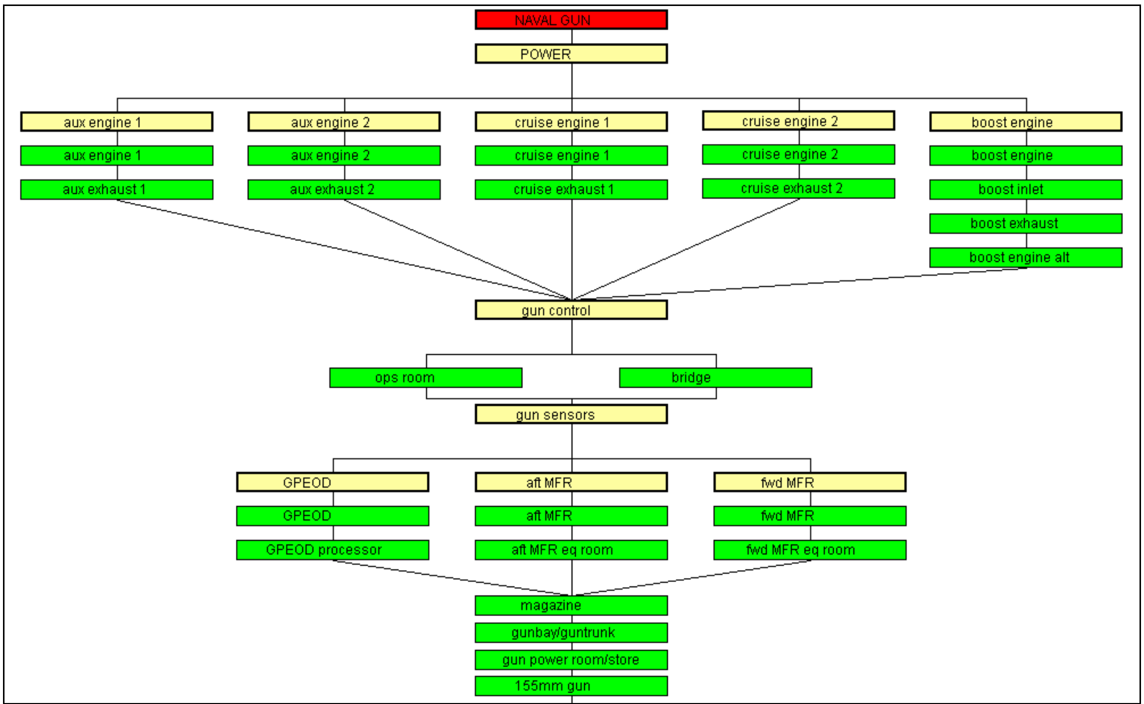


Figure A50: Destroyer Medium Calibre Naval Gun System Tree Diagram

ASM System

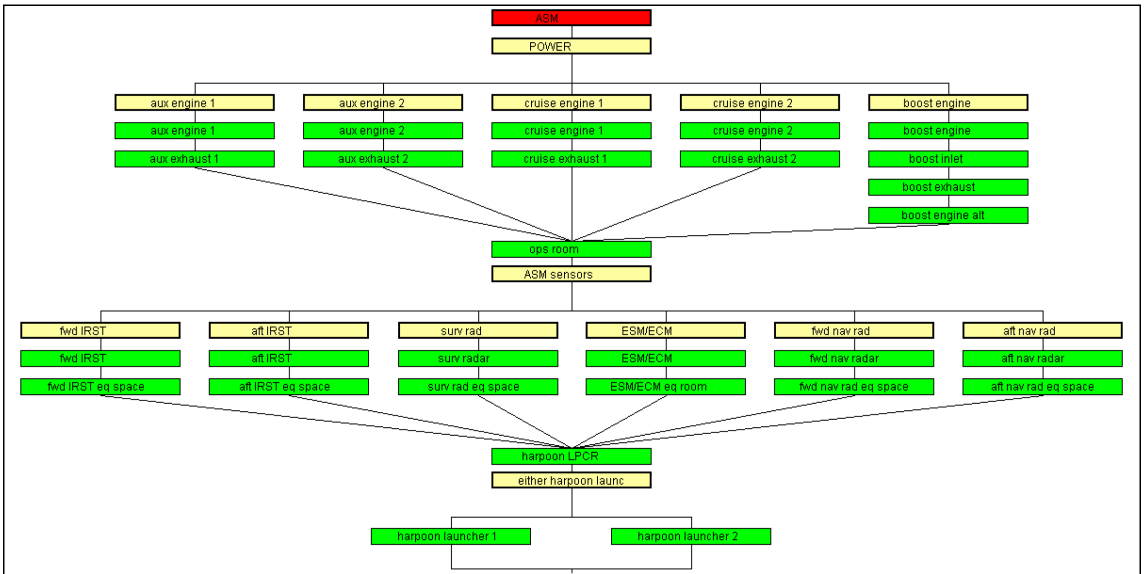


Figure A51: Frigate Variants 1, 2 and 3 and Corvette ASM System Tree Diagram

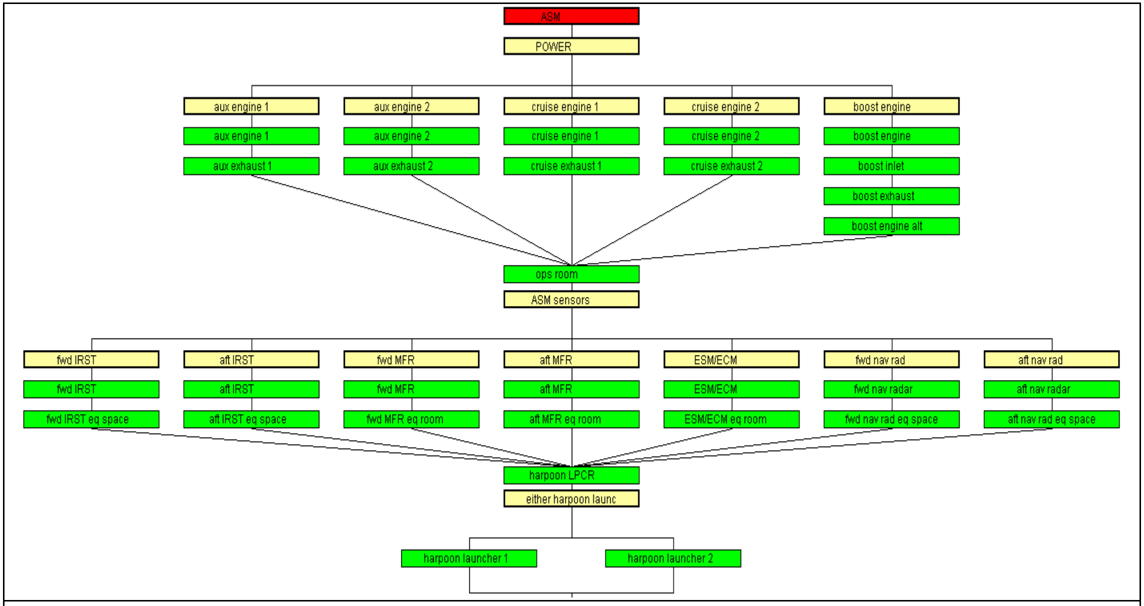


Figure A52: Destroyer ASM System Tree Diagram

Fwd/aft SAM Systems

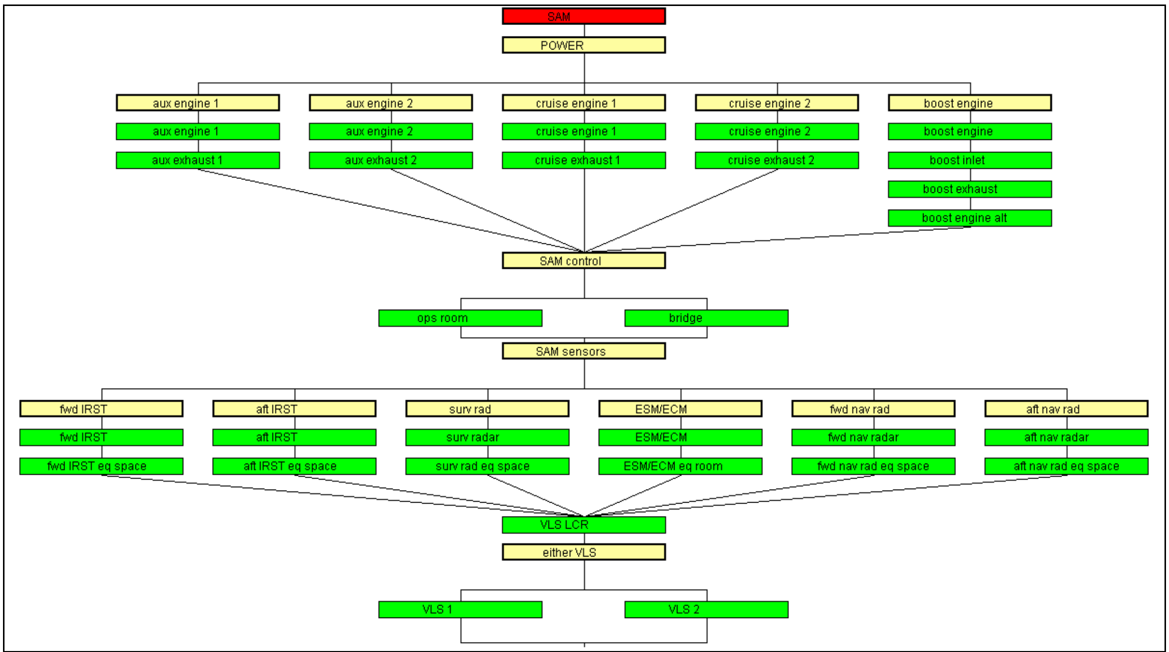


Figure A53: Frigate Variants 1, 2 and 3 and Corvettes fwd/aft SAM Systems Tree Diagram

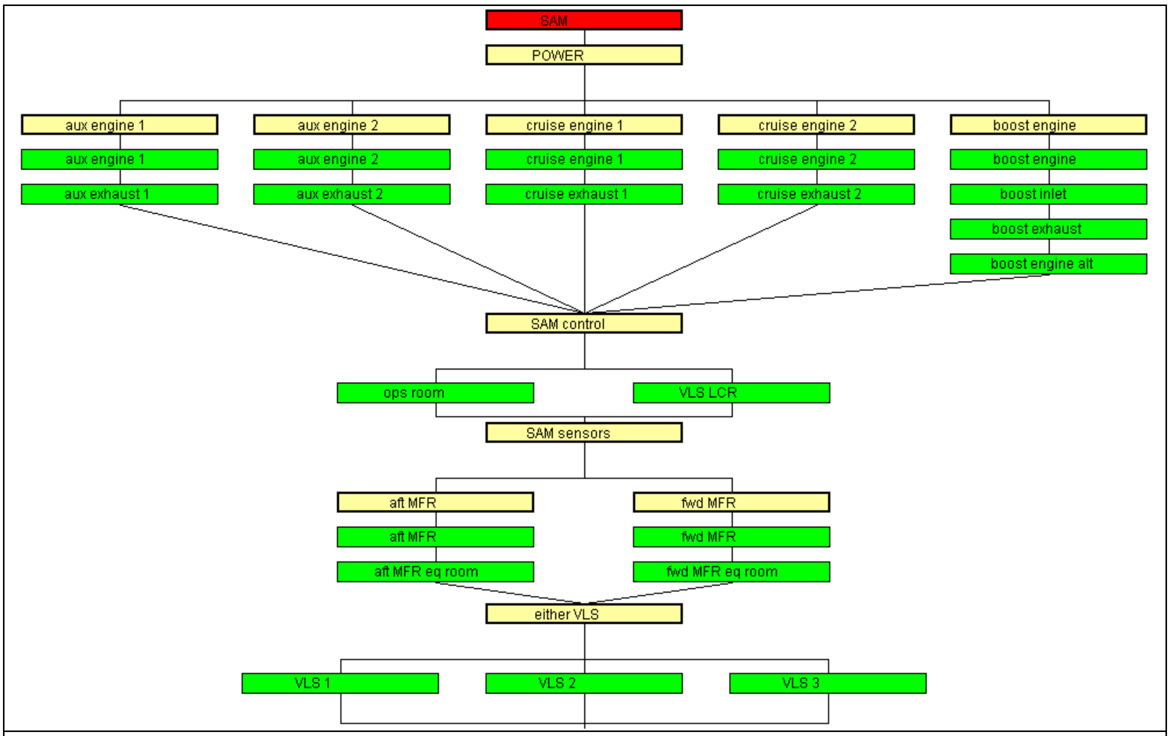


Figure A54: Destroyer fwd/aft SAM Systems Tree Diagram

Helicopter System

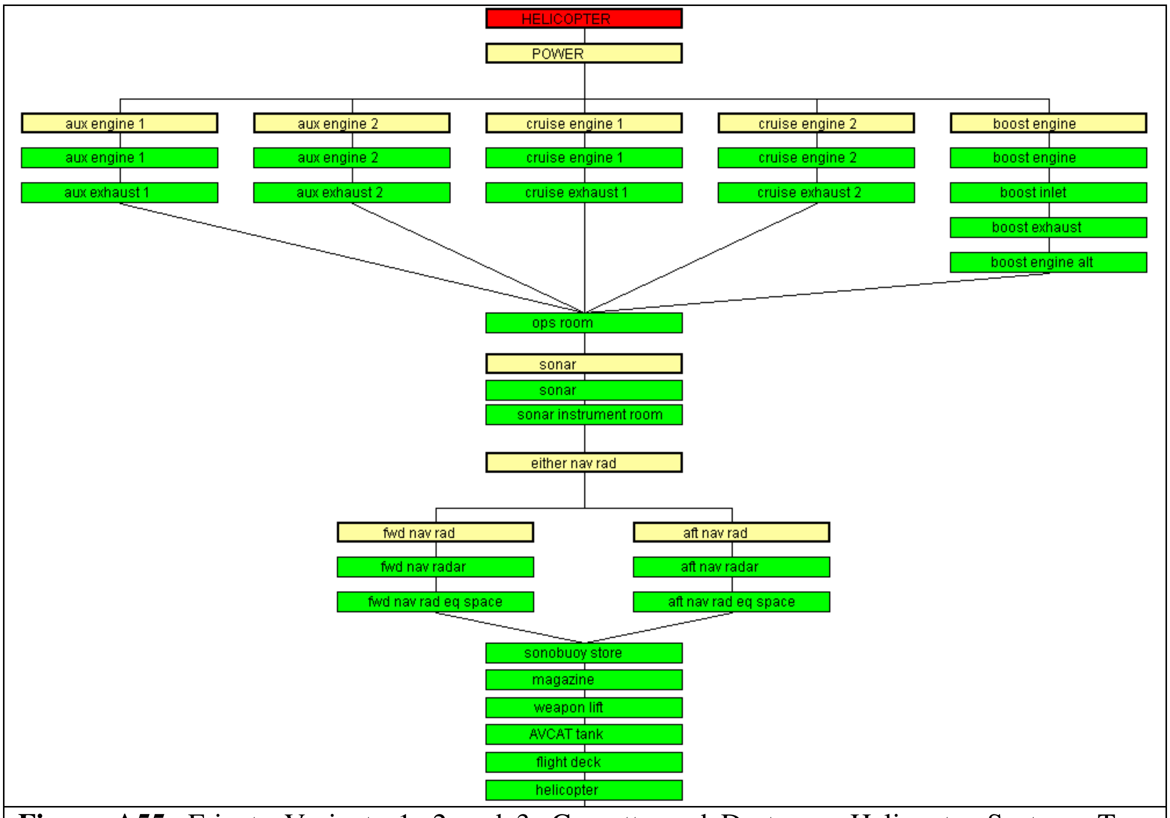


Figure A55: Frigate Variants 1, 2 and 3, Corvette and Destroyer Helicopter Systems Tree Diagram

A7.2 Combatant System Architecture

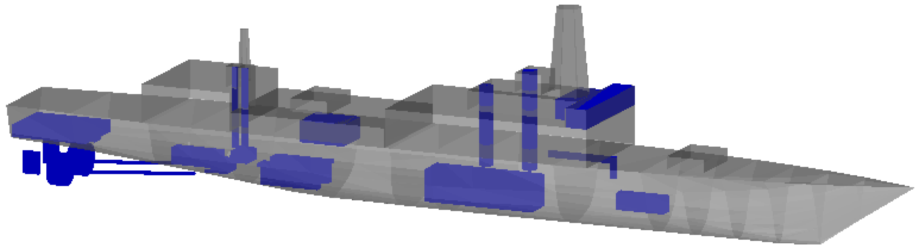
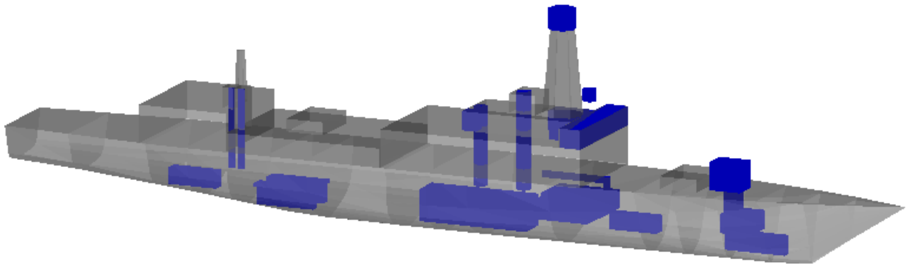
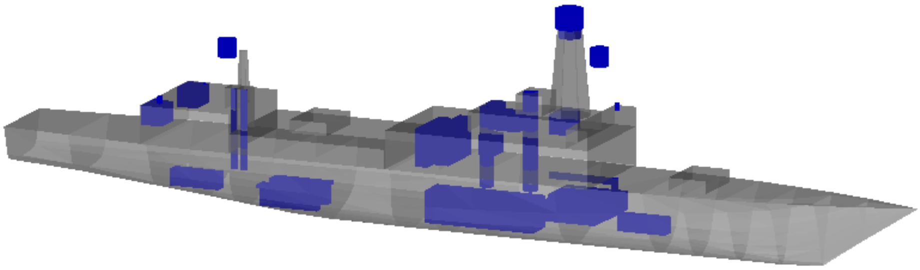
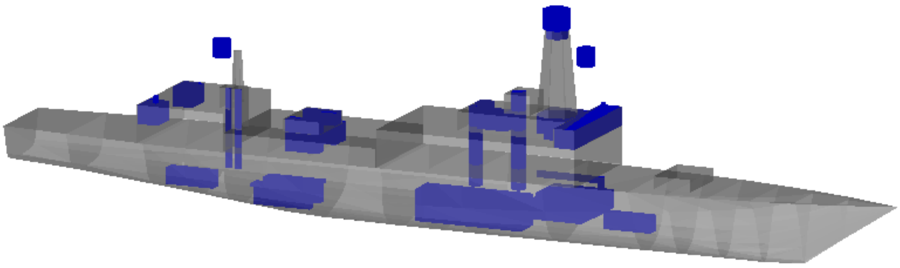
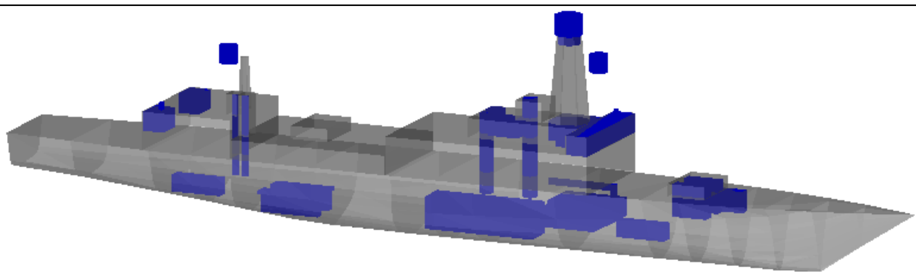
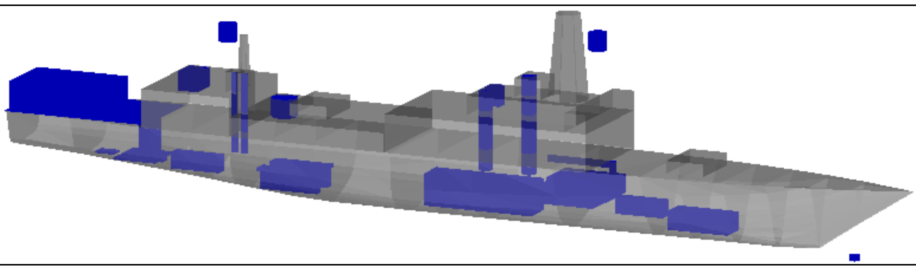
	Move System
	Medium Calibre Naval Gun System
	ASM System
	Aft SAM System
	Fwd SAM System
	Helicopter System

Figure A56: Frigate Variant 1 System Architecture

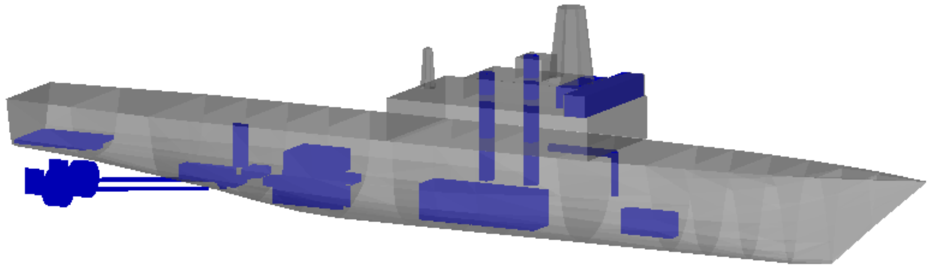
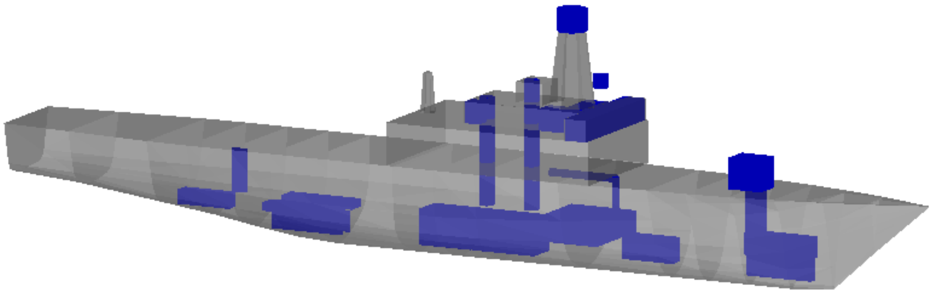
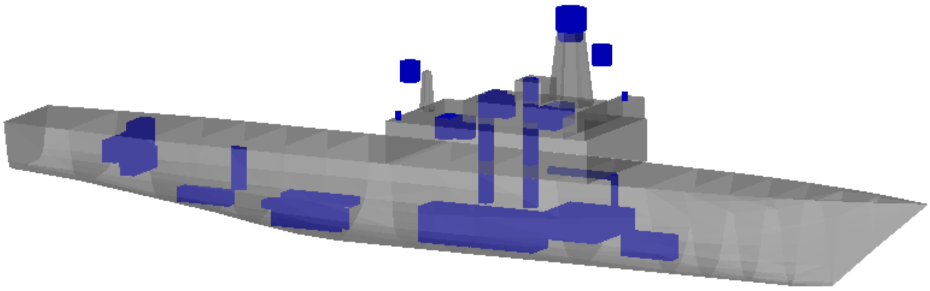
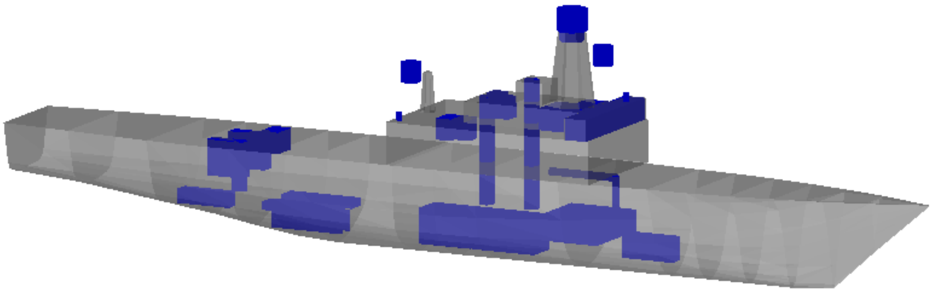
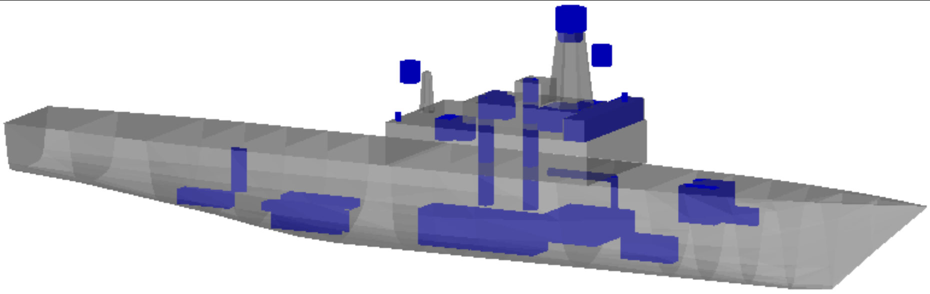
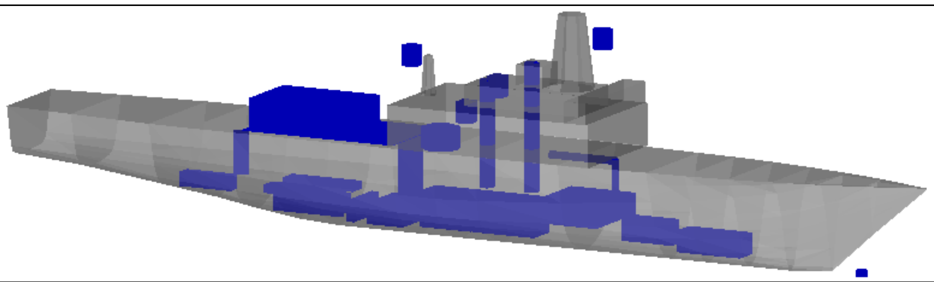
	Move System
	Medium Calibre Naval Gun System
	ASM System
	Aft SAM System
	Fwd SAM System
	Helicopter System

Figure A57: Frigate Variant 2 System Architecture

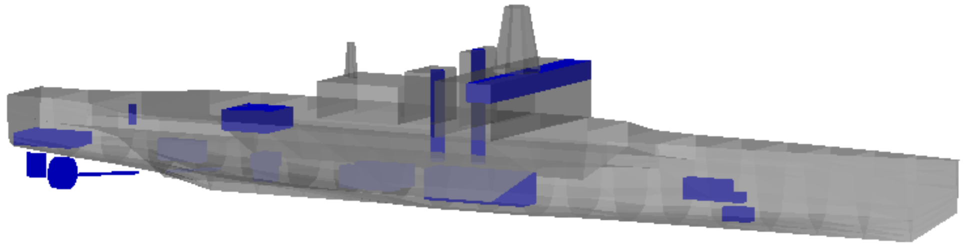
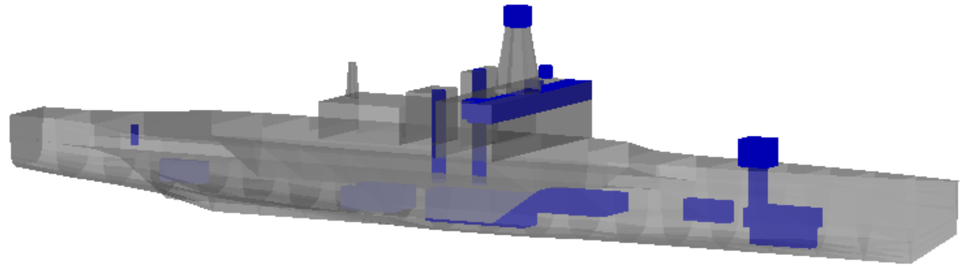
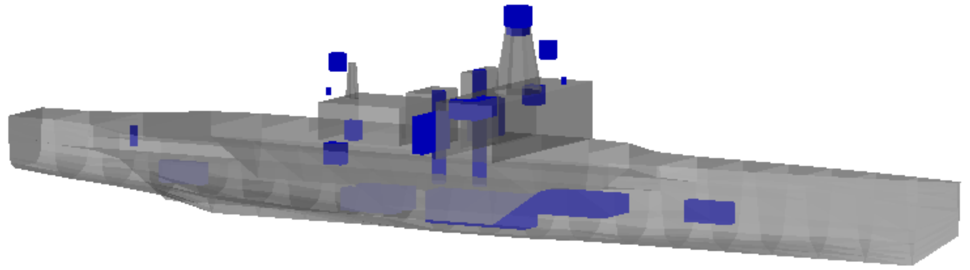
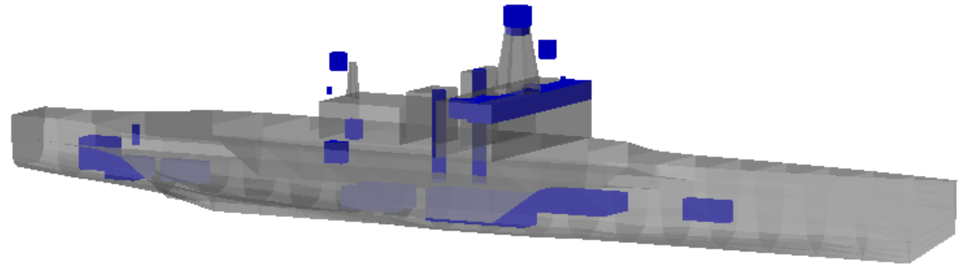
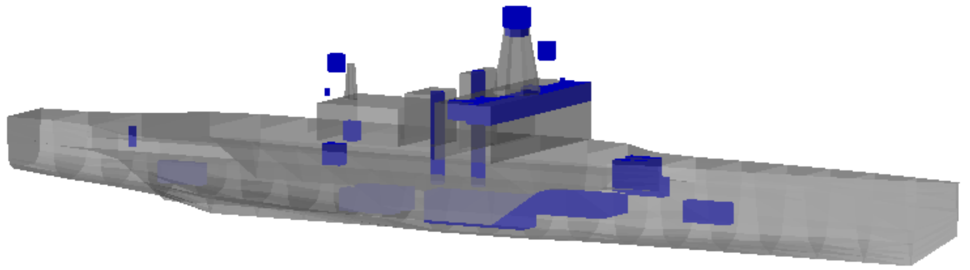
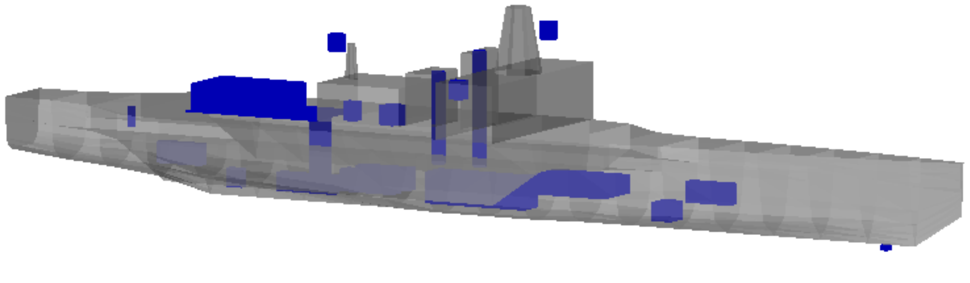
	Move System
	Medium Calibre Naval Gun System
	ASM System
	Aft SAM System
	Fwd SAM System
	Helicopter System

Figure A58: Frigate Variant 3 System Architecture

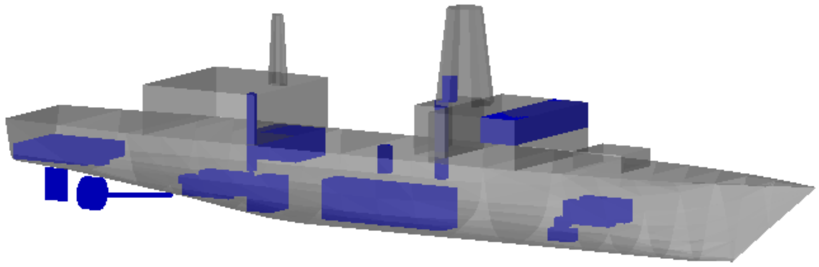
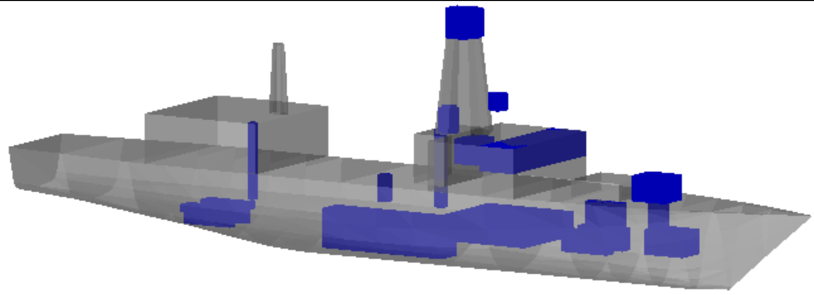
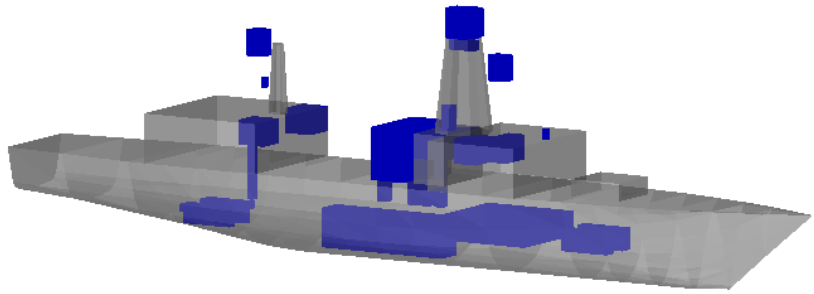
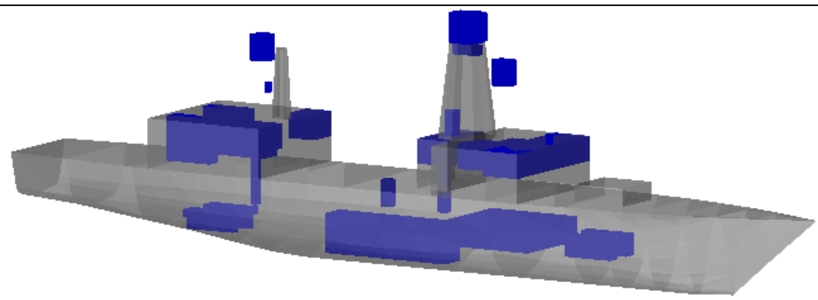
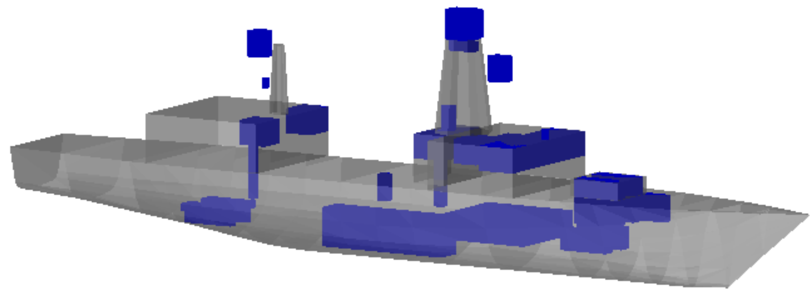
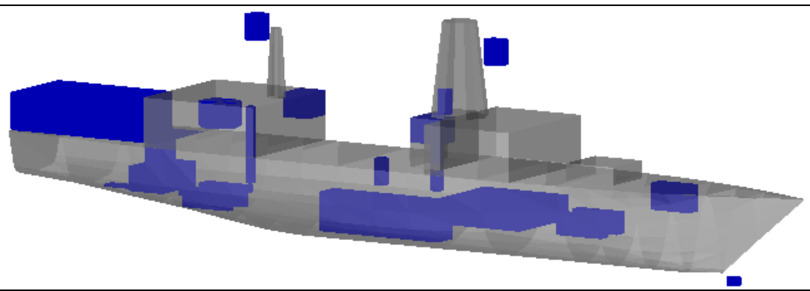
	Move System
	Medium Calibre Naval Gun System
	ASM System
	Aft SAM System
	Fwd SAM System
	Helicopter System

Figure A59: Corvette System Architecture

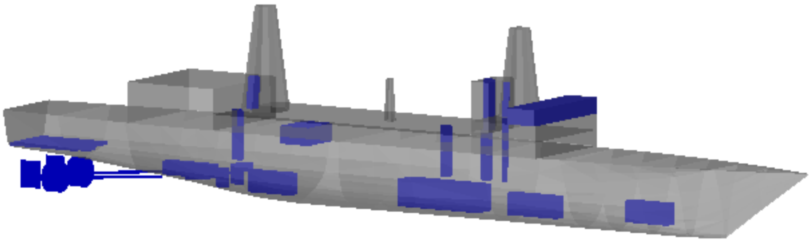
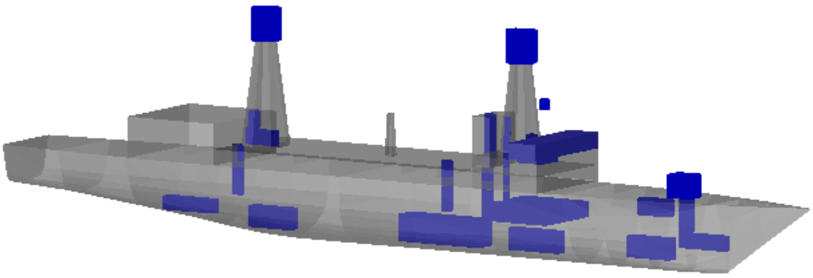
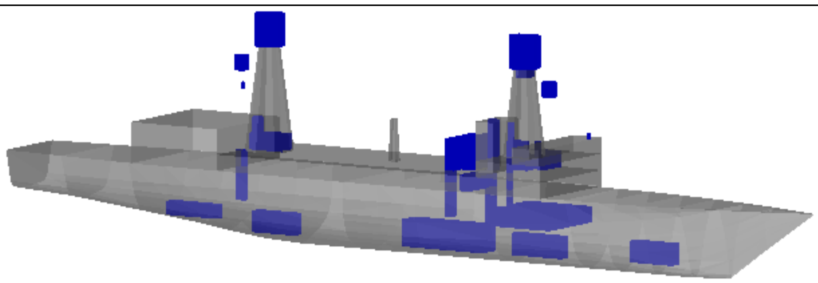
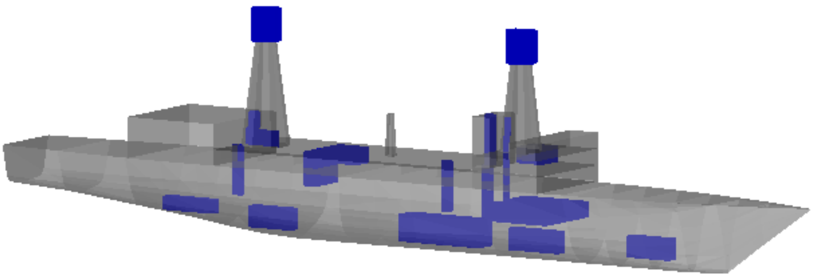
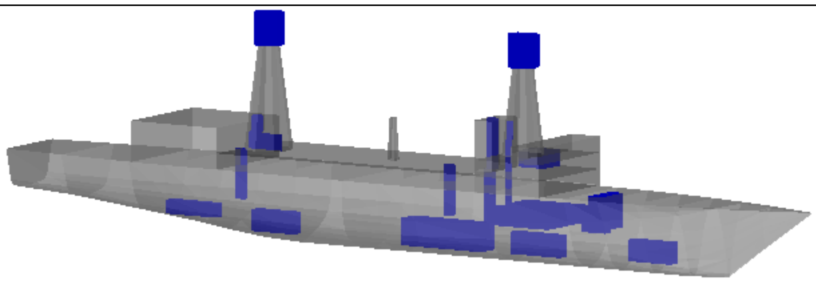
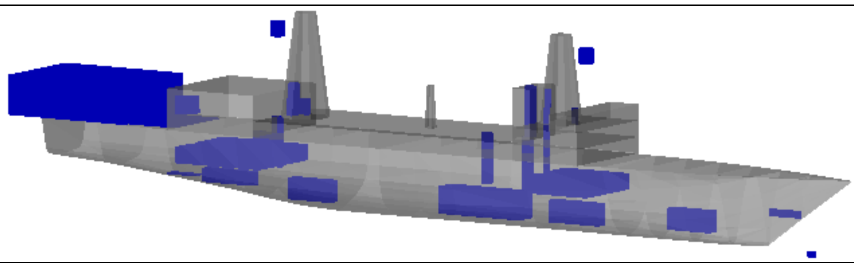
	Move System
	Medium Calibre Naval Gun System
	ASM System
	Aft SAM System
	Fwd SAM System
	Helicopter System

Figure A60: Destroyer System Architecture

A7.3 AOR System Tree Diagrams

Move System

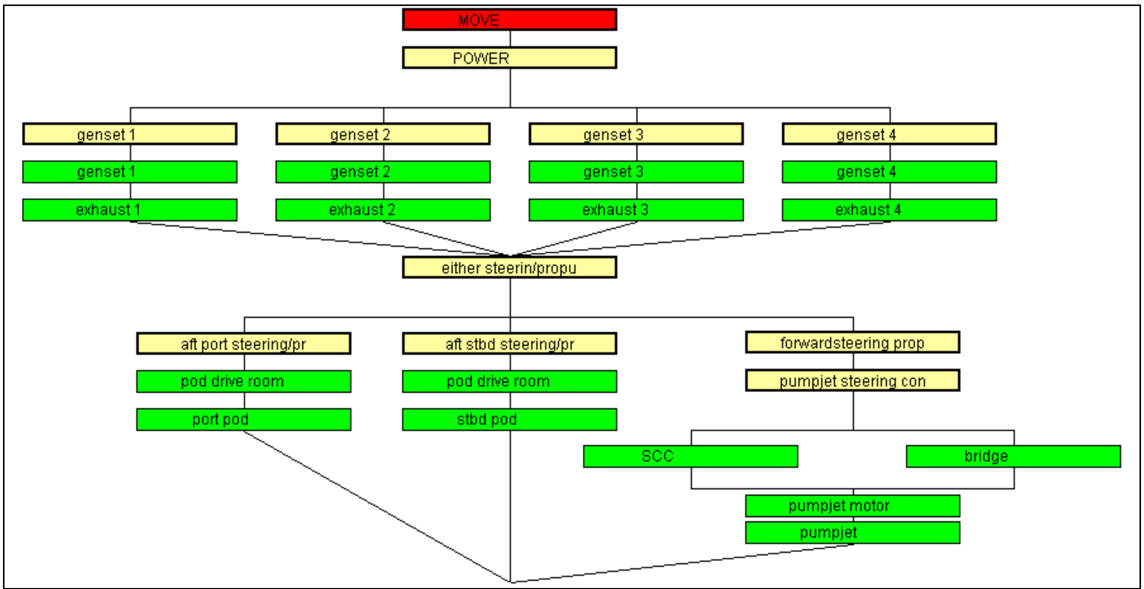


Figure A61: AOR Variant 1 Move System Tree Diagram

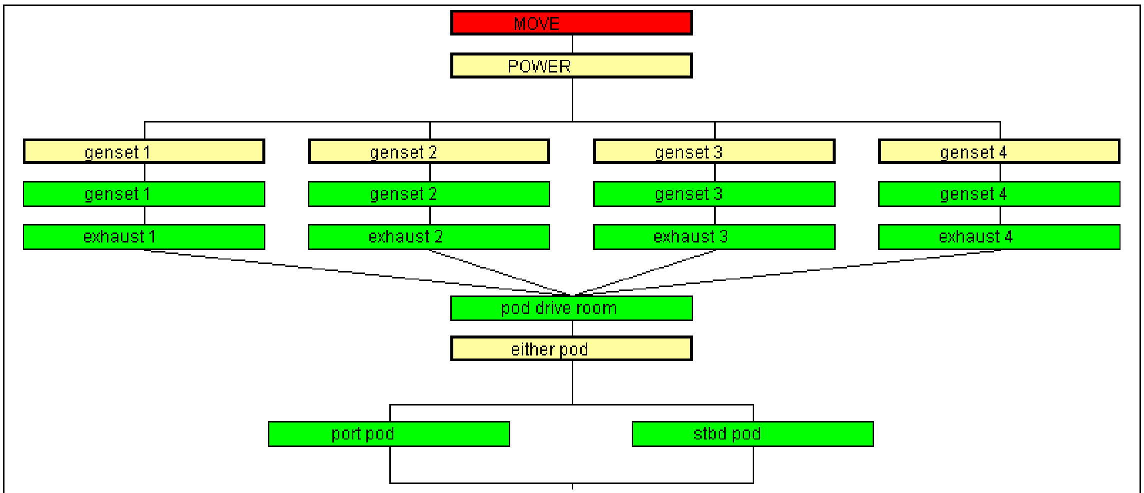


Figure A62: AOR Variant 2 Move System Tree Diagram

Ability to RAS AVCAT

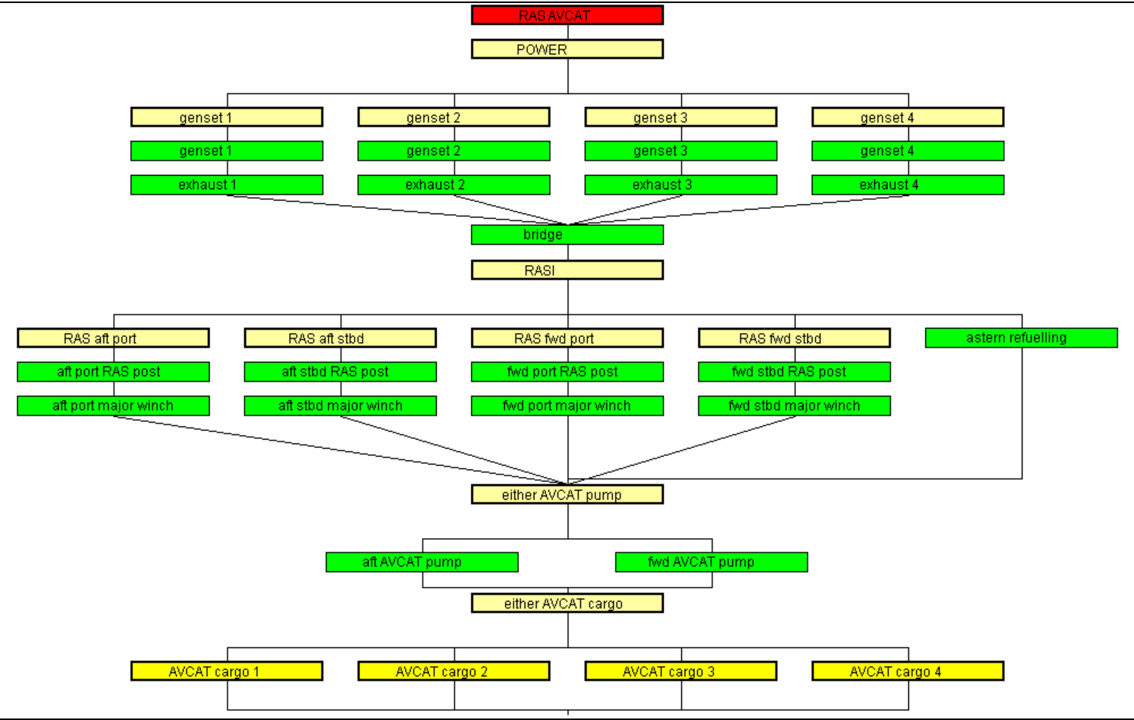


Figure A63: AOR Variant 1 Ability to RAS AVCAT Tree Diagram

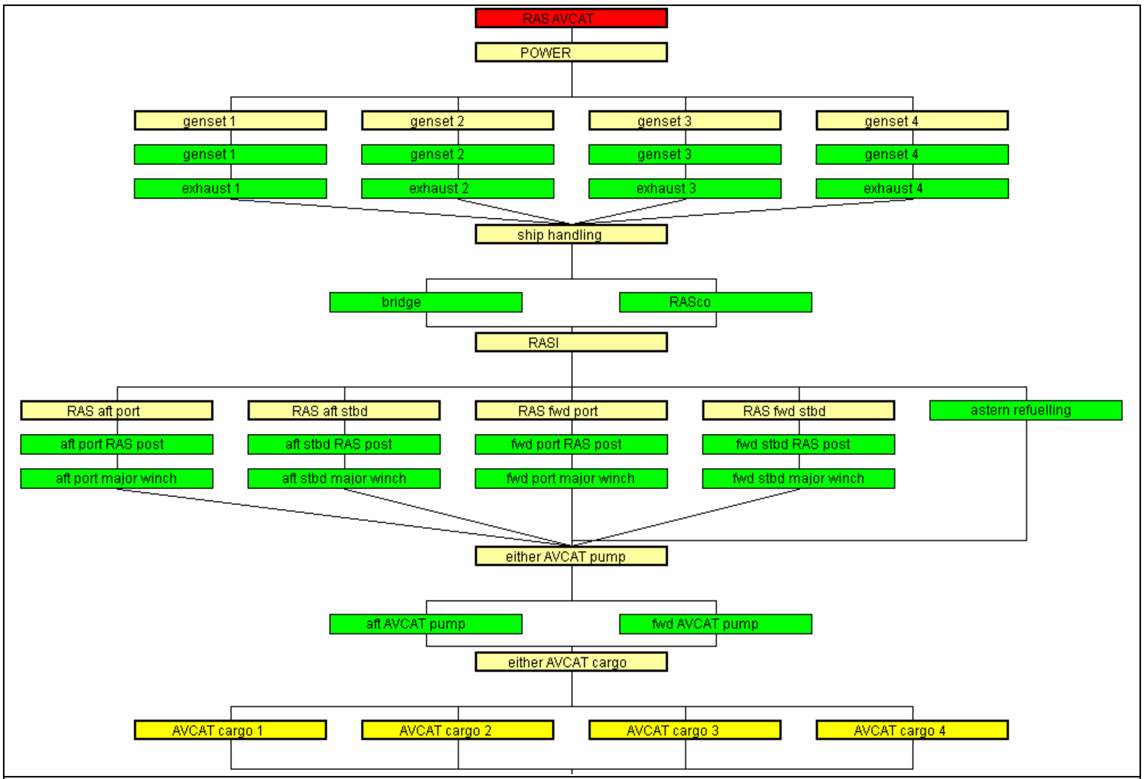


Figure A64: AOR Variant 2 Ability to RAS AVCAT Tree Diagram

Ability to RAS Dieso

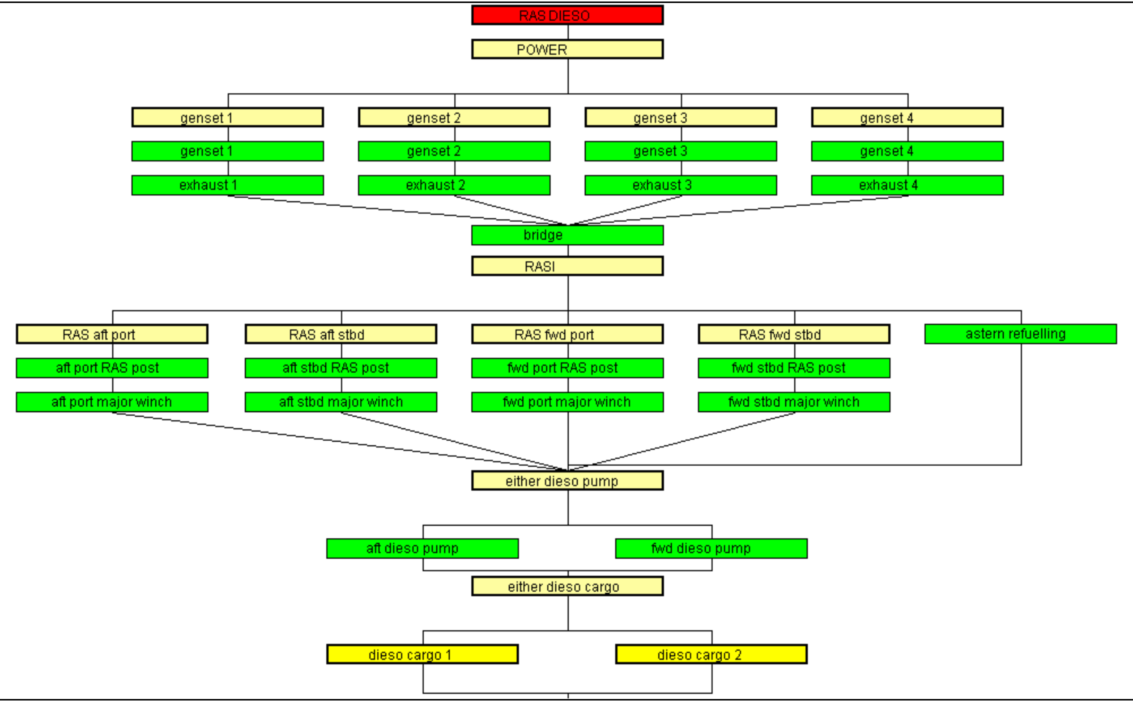


Figure A65: AOR Variant 1 Ability to RAS Dieso Tree Diagram

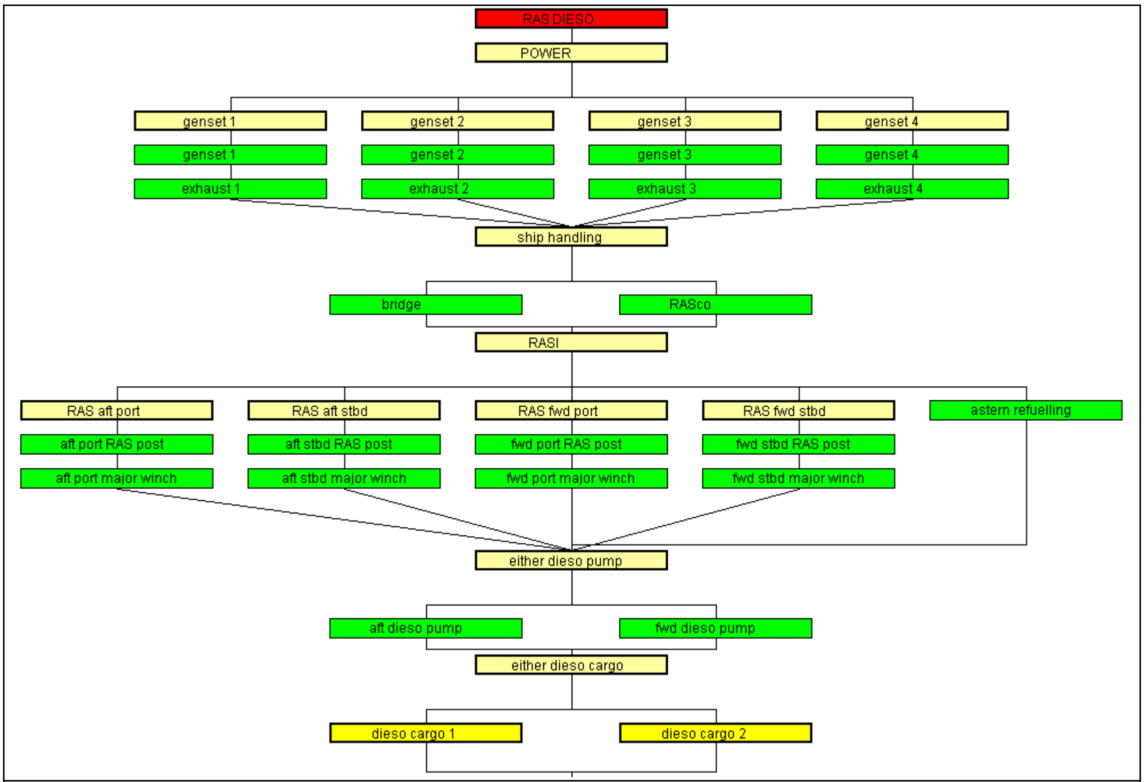


Figure A66: AOR Variant 2 Ability to RAS Dieso Tree Diagram

Ability to RAS Dry Stores

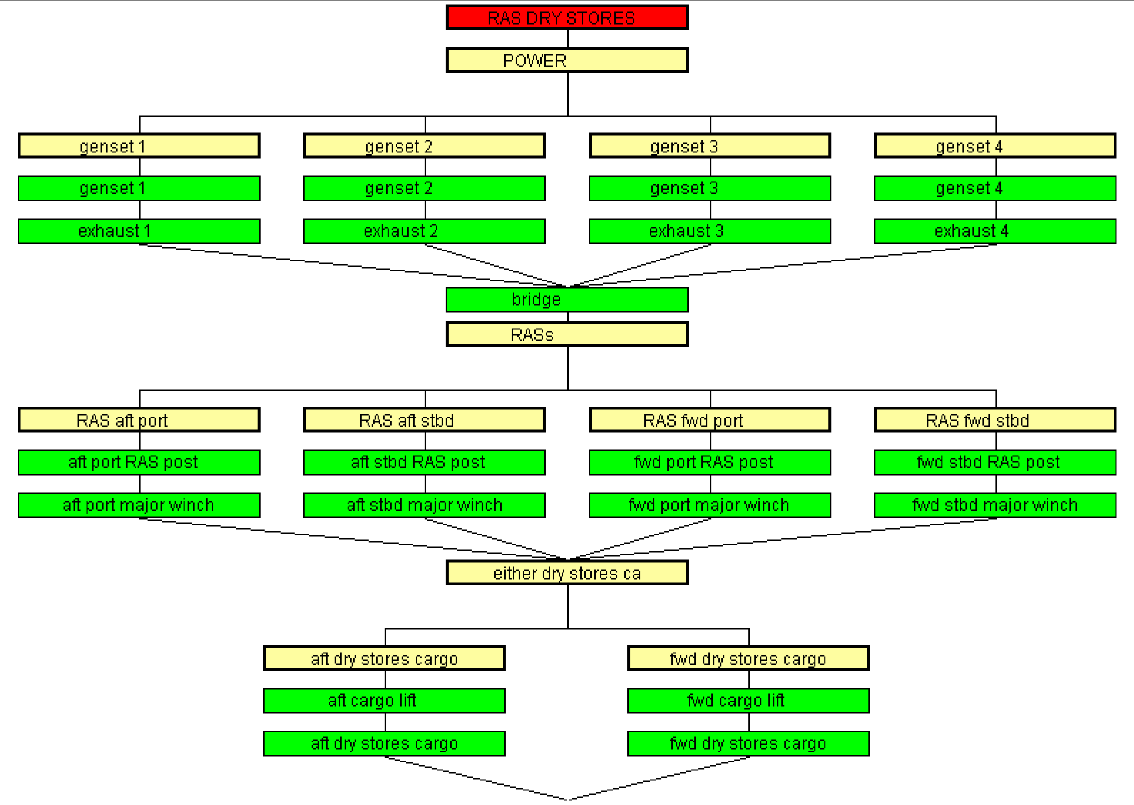


Figure A67: AOR Variant 1 Ability to RAS Dry Stores Tree Diagram

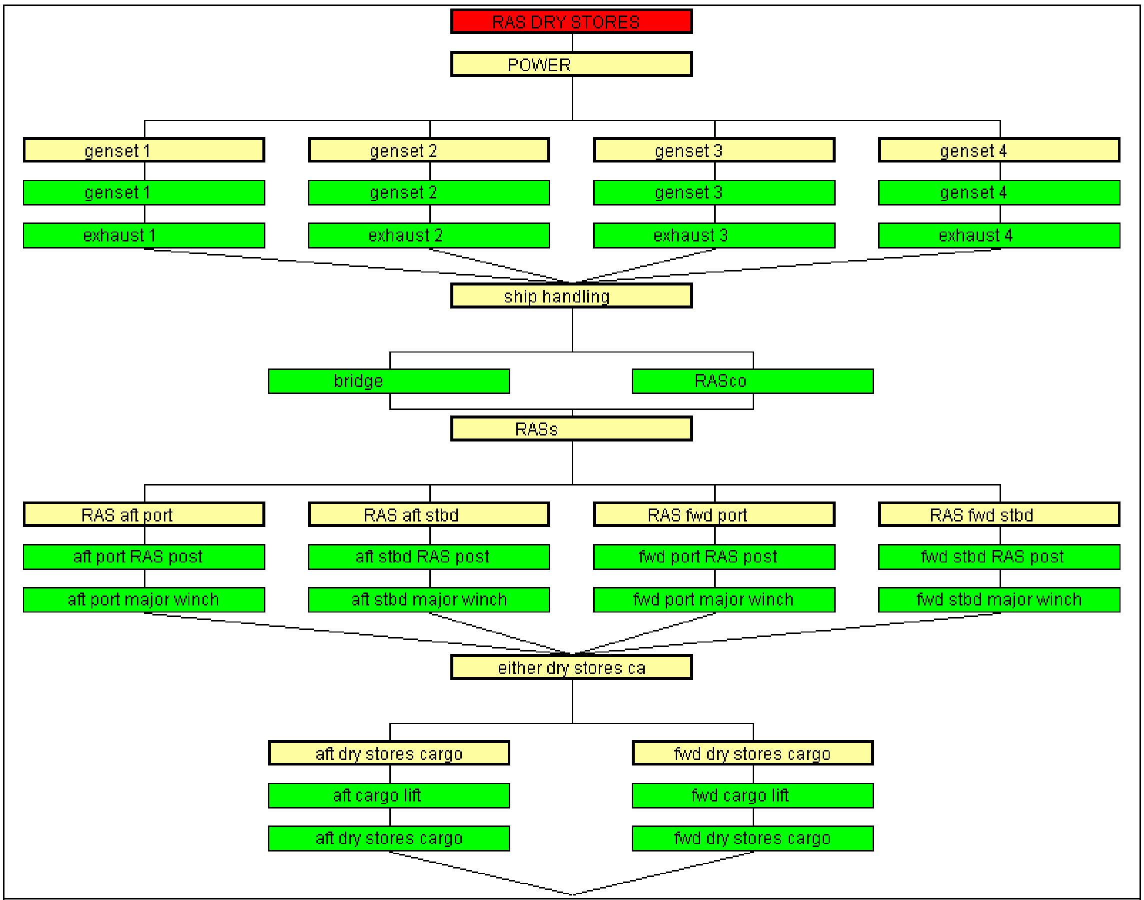


Figure A68: AOR Variant 2 Ability to RAS Dry Stores Tree Diagram

Ability to RAS Ordnance

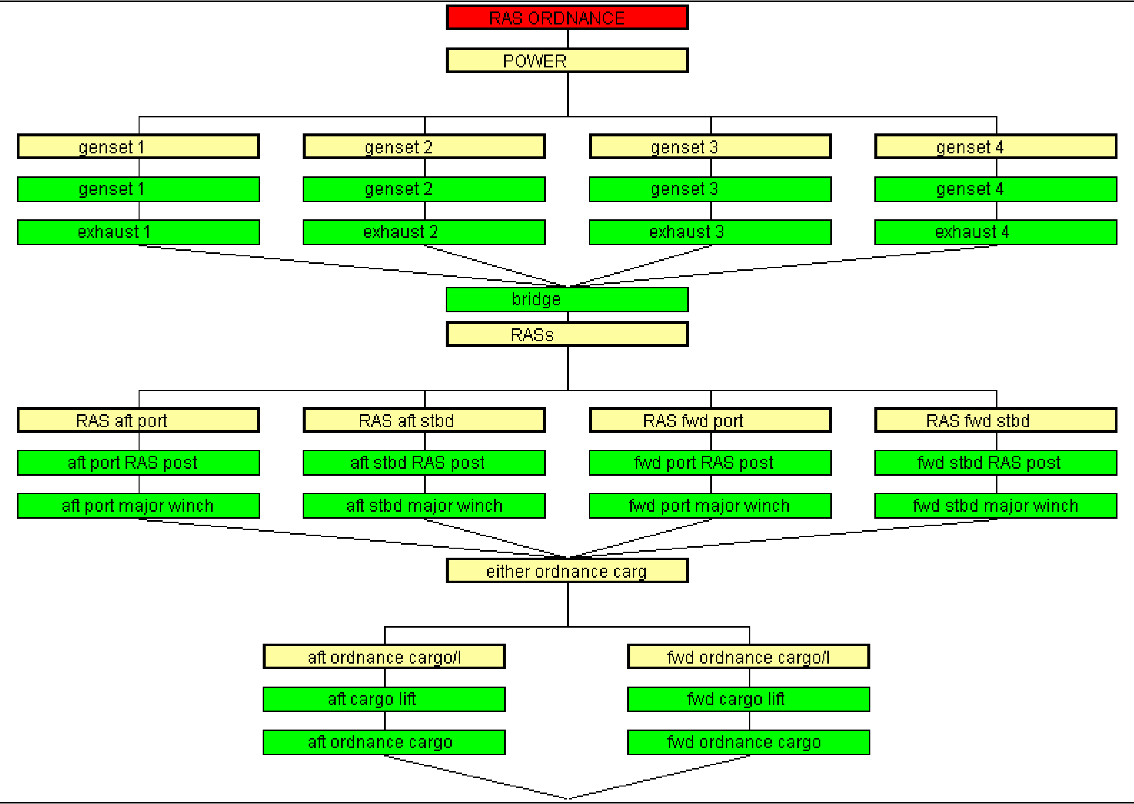


Figure A69: AOR Variant 1 Ability to RAS Ordnance Tree Diagram

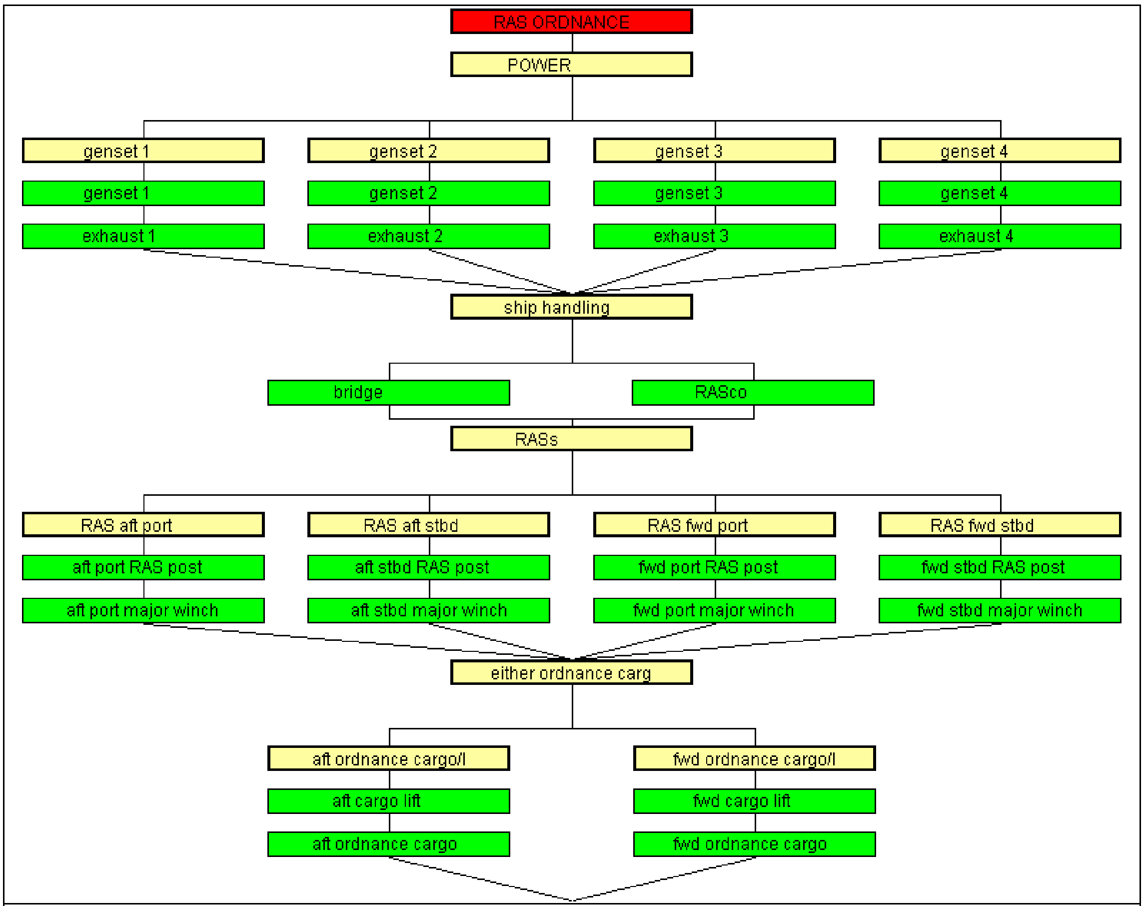


Figure A70: AOR Variant 2 Ability to RAS Ordnance Tree Diagram

Aviation Support System

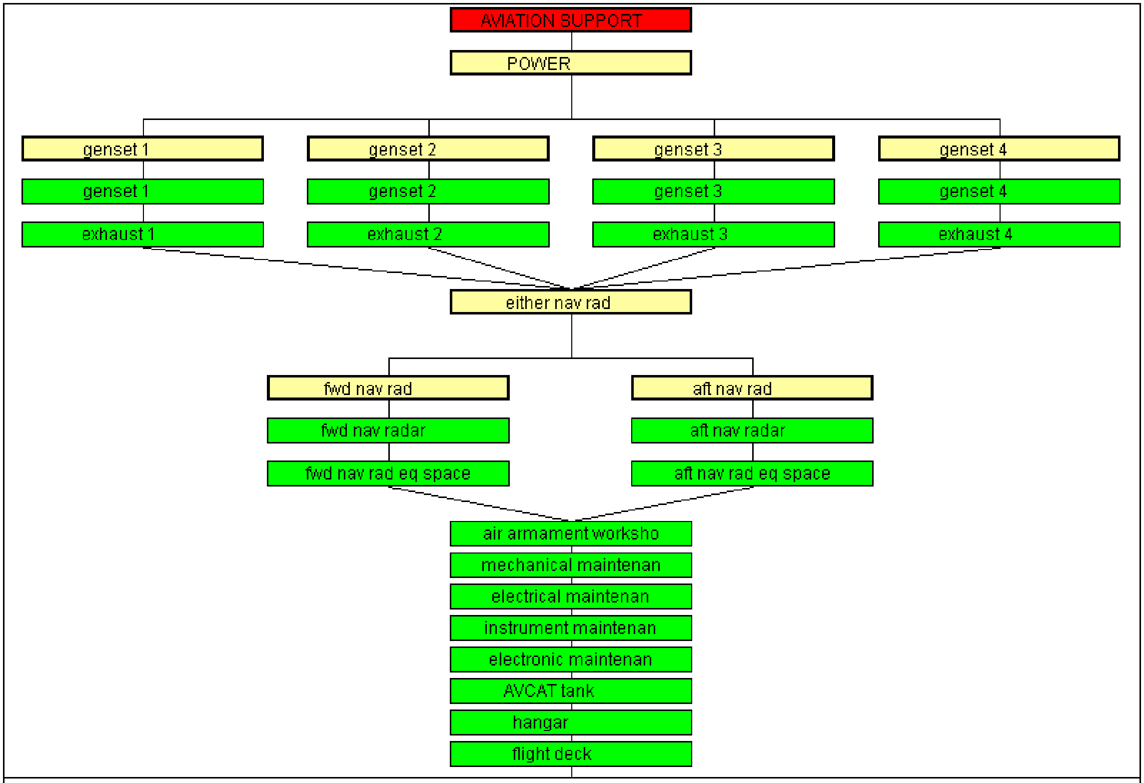


Figure A71: AOR Variants 1 and 2 Aviation Support System Tree Diagram

CIWS

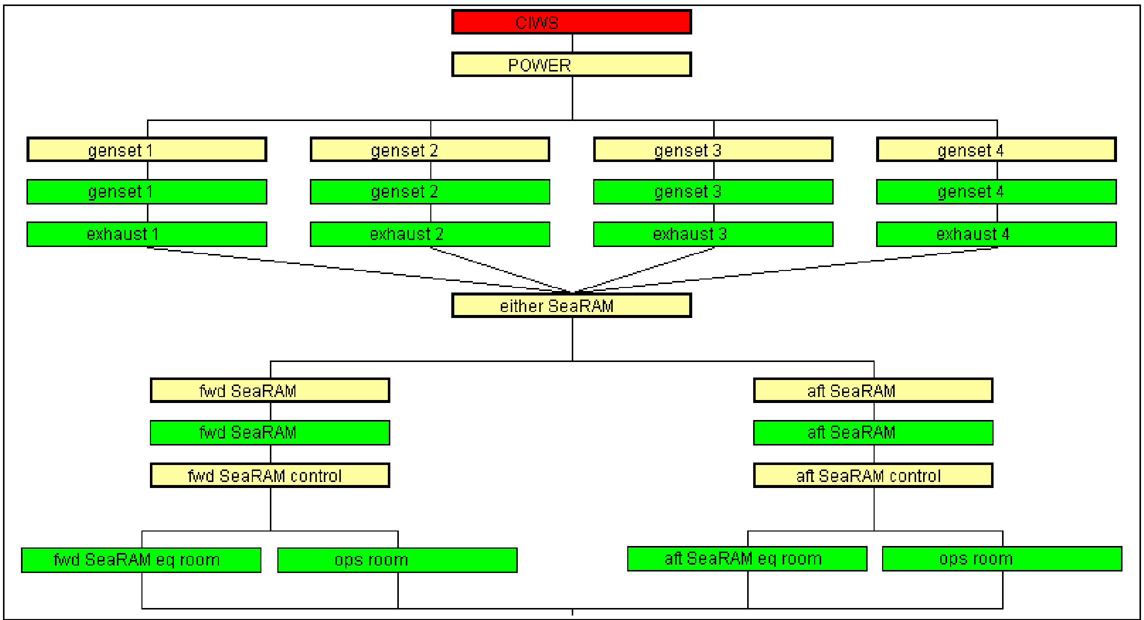


Figure A72: AOR Variants 1 and 2 CIWS Tree Diagram

A7.4 AOR System Architecture

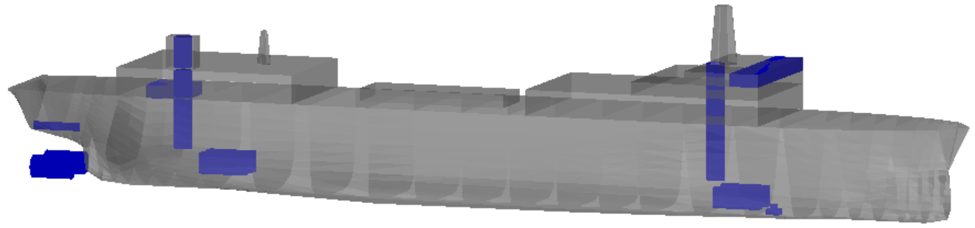
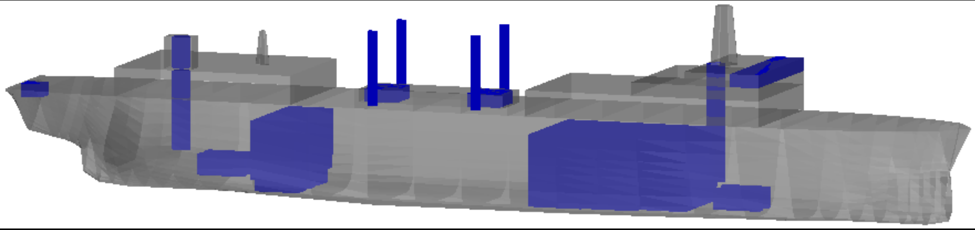
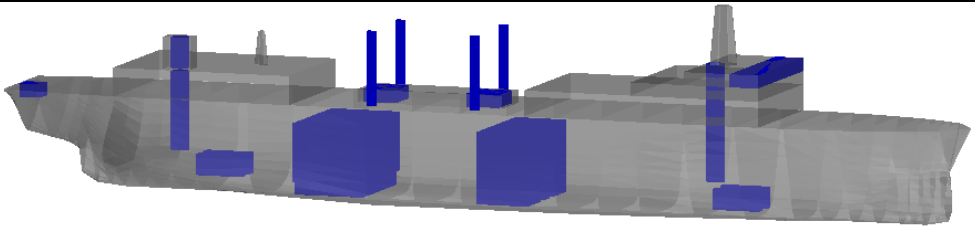
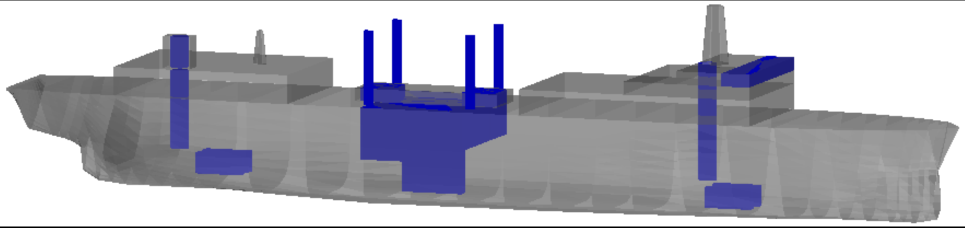
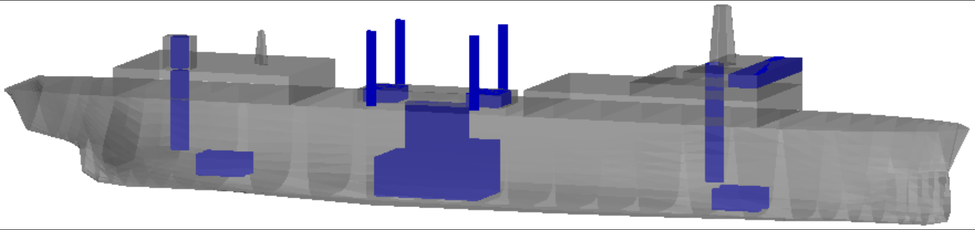
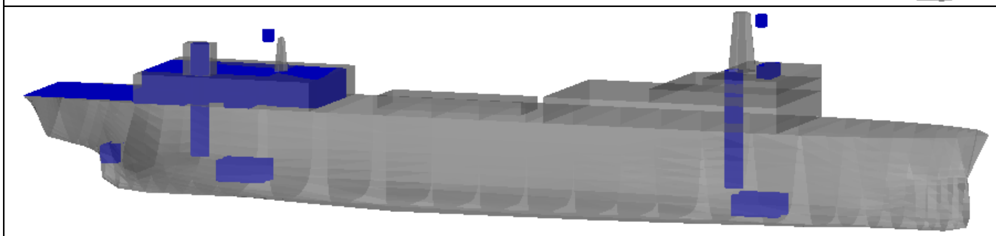
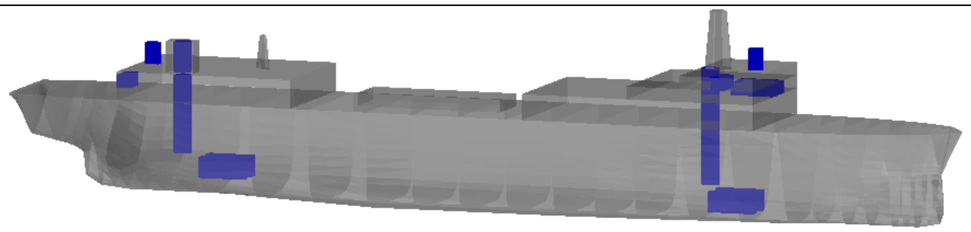
	Move System
	Ability to RAS AVCAT
	Ability to RAS Dieso
	Ability to RAS Dry Stores
	Ability to RAS Ordnance
	Aviation Support System
	CIWS

Figure A73: AOR Variant 1 System Architecture

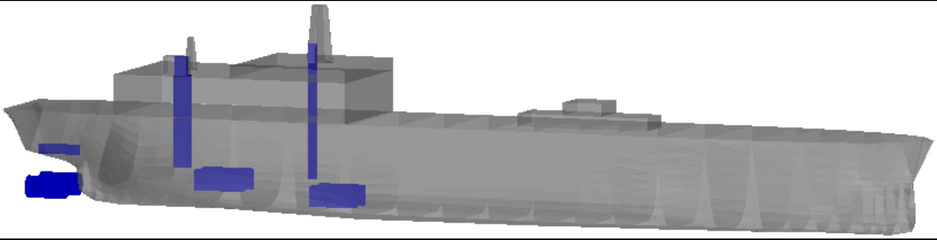
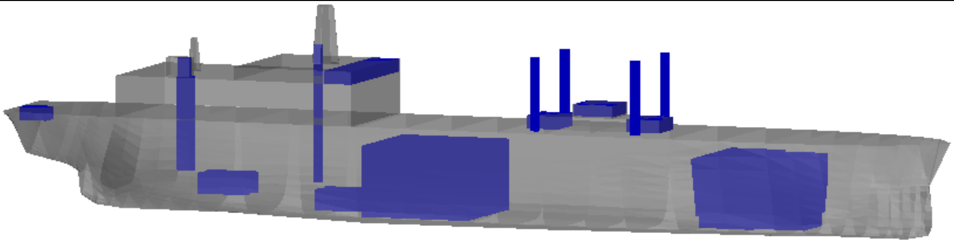
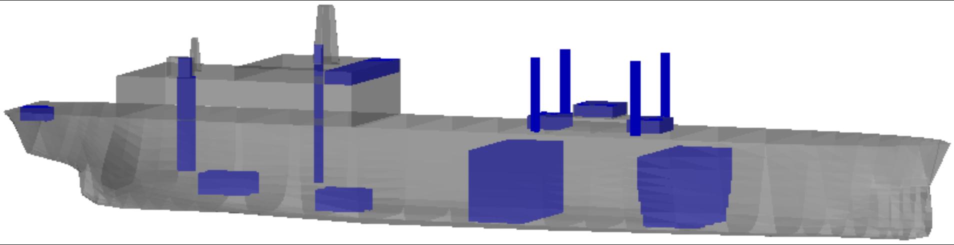
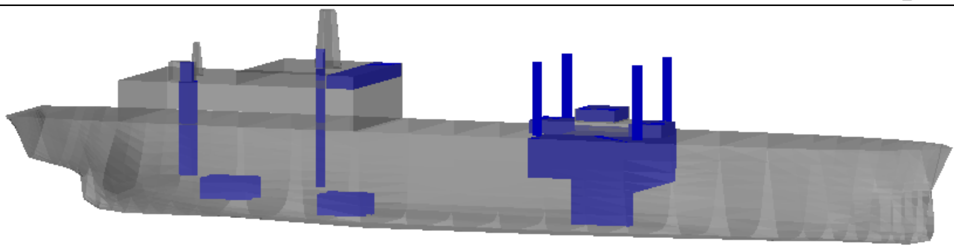
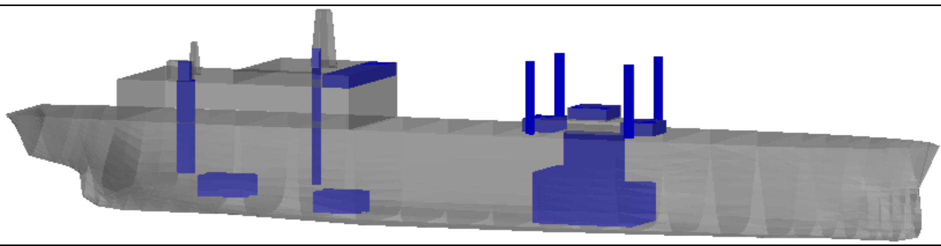
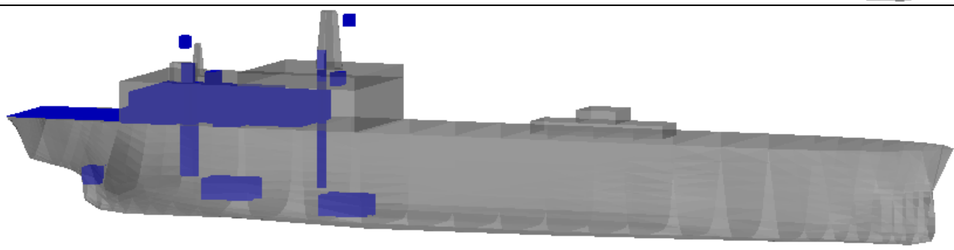
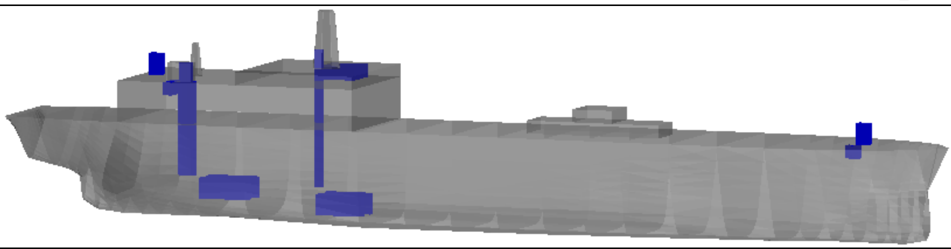
	Move System
	Ability to RAS AVCAT
	Ability to RAS Dieso
	Ability to RAS Dry Stores
	Ability to RAS Ordnance
	Aviation Support System
	CIWS

Figure A74: AOR Variant 2 System Architecture

Appendix 8: General Arrangements

A8.1 Frigate Variant 1

Provided in attached CD ROM (inside cover)

A8.2 Frigate Variant 2

Provided in attached CD ROM (inside cover)

A8.3 Frigate Variant 3

Provided in attached CD ROM (inside cover)

A8.4 Corvette

Provided in attached CD ROM (inside cover)

A8.5 Destroyer

Provided in attached CD ROM (inside cover)

A8.6 AOR Variant 1

Provided in attached CD ROM (inside cover)

A8.7 AOR Variant 2

Provided in attached CD ROM (inside cover)

Appendix 9: Ship Design Studies Data

A9.1 Complement and Accommodation Requirements

This appendix defines the complement and accommodation requirements (including margins and embarked forces) for the ship design studies developed.

Frigate Variants (Including Baseline)

Table A2: Frigate Variant 1 Accommodation Breakdown						
	CO	**Officers**	**CPO**	**PO**	**JR**	**Total**
Complement	1	9	12	17	86	**125**
Training and advancement margin	0	1	1	1	6	**9**
Board margin	0	0	3	3	8	**14**
Embarked Forces	0	2	4	0	19	**25**
Total	**1**	**12**	**20**	**21**	**119**	**173**

Table A3: Frigate Variant 2 Accommodation Breakdown						
	CO	**Officers**	**CPO**	**PO**	**JR**	**Total**
Complement	1	9	13	17	87	**127**
Training and advancement margin	0	1	1	1	7	**10**
Board margin	0	0	3	3	9	**15**
Embarked Forces	0	2	4	0	19	**25**
Total	**1**	**12**	**21**	**21**	**122**	**177**

Table A4: Frigate Variant 3 Accommodation Breakdown						
	CO	**Officers**	**CPO**	**PO**	**JR**	**Total**
Complement	1	10	14	18	94	**137**
Training and advancement margin	0	1	1	2	7	**11**
Board margin	0	0	3	3	10	**16**
Embarked Forces	0	2	4	0	19	**25**
Total	**1**	**13**	**22**	**23**	**130**	**189**

Since the relationship used to estimate accommodation requirements scaled with displacement, the three frigate design variants have slight different complements. However, all three variants perform the same role and have the same payload; therefore, it could be argued that they should have identical crews. Nonetheless, an in depth study of frigate manning was not conducted as it was seen to be beyond the scope of this research.

Corvette and Destroyer

Table A5: Corvette Accommodation Breakdown						
	CO	**Officers**	**CPO**	**PO**	**JR**	**Total**
Complement	1	8	8	11	35	**63**
Training and advancement margin	0	1	1	1	2	**5**
Board margin	0	0	1	1	4	**6**
Embarked Forces	0	0	0	0	0	**0**
Total	**1**	**9**	**10**	**13**	**41**	**74**

Table A6: Destroyer Accommodation Breakdown						
	CO	**Officers**	**CPO**	**PO**	**JR**	**Total**
Complement	1	17	19	26	75	**138**
Training and advancement margin	0	2	2	2	8	**14**
Board margin	0	2	3	3	13	**21**
Embarked Forces	0	4	8	0	38	**50**
Total	**1**	**25**	**32**	**31**	**134**	**223**

AOR Variants

Table A7: AOR Accommodation Breakdown					
	CO	**Officers**	**SR**	**JR**	**Total**
Complement	1	25 (11RFA + 14 RN)	55 (27 RFA + 28 RN)	105 (78 RFA + 27 RN)	**186**
Training and advancement margin		2 (1 RFA + 1 RN)	4 (1 RFA + 3 RN)	6 (2 RFA + 4 RN)	**12**
Board margin		2 (1 RFA + 1 RN)	4 (2 RFA + 2 RN)	9 (6 RFA + 3 RN)	**15**
Total	**1**	**29**	**63**	**120**	**213**

Note the sizable RN crew, mainly resulting from the aviation support requirement, as well as helicopter and combat operations. Different accommodation standards were used for RN and RFA crews, as suggested by (UCL 2010b).

A9.2 Weight Breakdown

This appendix includes weight data at the deep condition including all margins and seating's for the ship design studies developed. The UCL Ship Design Exercise weight (and space) classification system was used for all design studies. Group 8 refers to board and growth margins, rather than design and construction margins (see Appendix 1), which are incorporated within their individual group weights.

Frigate Variants (Including Baseline)

Table A8: Frigate Variant 1 Top Level Weight Breakdown				
	Weight (te)	**Centroid x (m)**	**Centroid y (m)**	**Centroid z (m)**
Total	3,888.287	-5.428	-0.001	5.653
1 hull	1,875.463	-6.106	0.032	6.376
2 personnel	133.550	10.521	-0.057	9.060
3 ship systems	312.118	-6.745	-0.068	6.216
4 main propulsion	454.293	-19.421	0.088	3.461
5 electric power	141.985	-4.099	0.000	7.839
6 payload	137.448	17.113	-0.387	10.017
7 variable	619.589	-1.831	-0.007	1.967
8 margins	213.840	-5.666	0.004	7.240

Table A9: Frigate Variant 2 Top Level Weight Breakdown				
	Weight (te)	**Centroid x (m)**	**Centroid y (m)**	**Centroid z (m)**
Total	4,063.290	-4.866	-0.002	5.706
1 hull	1,982.826	-4.182	0.004	6.285
2 personnel	136.392	13.365	-0.058	9.665
3 ship systems	312.004	-3.646	-0.070	6.605
4 main propulsion	511.413	-18.666	0.011	3.473
5 electric power	143.591	-2.220	0.000	7.704
6 payload	137.729	19.331	-0.450	10.837
7 variable	613.657	-6.657	0.120	2.210
8 margins	225.677	-3.886	-0.017	7.150

Table A10: Frigate Variant 3 Top Level Weight Breakdown				
	Weight (te)	**Centroid x (m)**	**Centroid y (m)**	**Centroid z (m)**
Total	4,334.841	-4.18	0.006	6.869
1 hull	2,183.548	-6.971	0.092	7.995
2 personnel	145.448	8.185	-0.459	10.301
3 ship systems	339.847	-5.499	-0.413	7.187
4 main propulsion	477.097	-14.237	-0.002	4.311
5 electric power	162.463	-6.347	0.000	7.825
6 payload	136.164	12.353	0.023	10.434
7 variable	640.609	8.001	0.051	2.543
8 margins	249.666	-4.825	-0.001	8.016

The main dissimilarity between the top level weight breakdowns of the three frigate variants is observed in the group 1 weight (which includes the ships structural weights). Both Frigate Variants 2 and 3 have larger group 1 weights than the baseline due to the larger group 1 weight margin used for these designs, as will be explained in Appendix 9.3. Additionally, the trimaran variant has a significantly larger gross volume compared to the other two ship designs (18,400m^3, 18,400m^3 and 20,840m^3 respectively) largely due to the many unused spaces in such hull configurations resulting from issues such as the very narrow side hull beam, the narrow aft and forward spaces in the main hull and the 3.5m air gap requirement (Andrews and Zhang 1995; Andrews 2004) as summarised in Appendix 2.2. The relationship used for the estimation of the structural weight was proportional to the gross volume of the ship, as given by (UCL 2010b):

$$\text{Structural weight} = 0.076\text{te} \times \text{ship gross volume} \times \text{group 1 weight margin} \qquad (11)$$

Therefore, this led to the trimaran having the highest group 1 weight. Since the complements of the frigate variants were sized based on current combatants' complement/displacement densities, Frigate Variant 3 had the largest complement (see Appendix 9.1), followed by Variant 2 and the baseline, this being reflected on the group 2 weights. In terms of group 4 weights, Frigate Variant 2 is the heaviest, due to the larger power system required to achieve the 30kt maximum speed requirement (see Appendix 9.4). The weights of group 6 are almost identical for all variants, which was expected, due to the identical payloads (Table 5.1). The differences between the weights of group 7 are almost entirely due to the fuel carried by each ship design to meet the minimum range requirement of 7,000nm at 15kts (Table 5.2), and secondarily due to the water and provision stores required, which scale with crew size. The difference in the weights of groups 3 and 5 are accounted for by the fact that the weight (and space) relationships of these groups given in (UCL 2010b) are largely proportional to the ships volume, therefore, leading to the trimaran being the heaviest ship design in these weight groups, with the other two variants presenting almost identical weights. Finally the differences in the group 8 weights, which refer to growth and board margins, are due to the fact that these margin types scale with lightships weight.

Corvette and Destroyer

Table A11: Corvette Top Level Weight Breakdown				
	Weight (te)	**Centroid x (m)**	**Centroid y (m)**	**Centroid z (m)**
Total	1,832.636	-4.396	0.012	5.155
1 hull	866.695	-4.705	0.057	5.668
2 personnel	50.288	-4.6	0.339	7.238
3 ship systems	184.013	-3.7	-0.47	5.332
4 main propulsion	280.114	-6.309	-0.017	2.909
5 electric power	63	-2.836	0	6.508
6 payload	91.535	3.384	0.095	9.72
7 variable	189.496	-5.184	0.202	2.085
8 margins	107.495	-4.168	-0.007	6.323

Table A12: Destroyer Top Level Weight Breakdown				
	Weight (te)	**Centroid x (m)**	**Centroid y (m)**	**Centroid z (m)**
Total	6,248.091	-5.52	0.005	7.016
1 hull	3,047.775	-7.072	-0.012	8.103
2 personnel	195.976	-4.081	-0.423	10.408
3 ship systems	455.06	-4.498	0.27	8.545
4 main propulsion	600.449	-13.338	0.104	3.317
5 electric power	235.165	-5.35	0	10.234
6 payload	251.858	12.365	-0.127	11.435
7 variable	1,126.769	-1.696	0	2.539
8 margins	335.04	-6.035	0.005	9.185

As anticipated, the larger the combatant, the larger the mass of each group. Given that the ship designs considered each belong to different ship types, therefore realising different sizes, crew numbers, power generation and distribution requirements, payloads, endurance requirements, etc. conclusions cannot be drawn from merely a weight comparison. This, once again, highlights the advantages of prioritising the visual functional breakdown (over the traditional weight breakdown) of a modern naval ship. It is interesting to note that for the structural weight estimation of the Corvette, the same relationship as for the remaining combatants (Equation 11) was used. Although it was initially used with hesitation, since it was thought that the Corvette would have a larger structural weight proportion, additional research was conducted and the resulting weight figure was confirmed using relationships found in (Usher and Dorey 1982).

AOR Variants

Table A13: AOR Variant 1 Top Level Weight Breakdown				
	Weight (te)	**Centroid x (m)**	**Centroid y (m)**	**Centroid z (m)**
Total	38,453.65	98.854	-0.004	11.084
1 hull	12,655.65	97.666	-0.022	13.051
2 personnel	280.944	130.145	0.199	21.711
3 ship systems	984.818	94.35	0.328	12.812
4 main propulsion	850.122	58.971	-0.253	7.165
5 electric power	695.888	98.509	0	14.707
6 payload	129.716	97.71	-0.892	16.062
7 variable	21,519.57	100.778	0.004	9.639
8 margins	1,336.948	101.535	-0.009	12.345

Table A14: AOR Variant 2 Top Level Weight Breakdown				
	Weight (te)	**Centroid x (m)**	**Centroid y (m)**	**Centroid z (m)**
Total	37,847.6	99.087	0.003	11.001
1 hull	12,432.39	90.452	0.004	13.032
2 personnel	280.944	65.988	0.399	20.672
3 ship systems	969.298	75.892	0.085	13.337
4 main propulsion	838.901	34.284	-0.232	7.389
5 electric power	681.342	89.604	0	14.7
6 payload	129.716	99.125	-0.615	16.296
7 variable	21,192.85	108.494	0.008	9.485
8 margins	1,322.163	99.546	-0.001	12.317

From the above two tables it is observed that AOR Variant 1 is slightly heavier, in the deep condition, that AOR Variant 2. The two main reasons for this are the increased cargo capacity previously analysed (group 7) (although, AOR Variant 2, unlike the first variant, required ballast water, which also belongs to group 7, in the deep condition, see Appendix 9.5), and the larger structural weight, part of group 1. Similarly to Equation 11, a relationship scaling with gross volume was used to compute the structural weights of the two variants. Although both hulls were identical, the split superstructures of Variant 1 combined were slightly larger than that that of the second variant, resulting to a gross volume of 95,320m^3 (compared to 92,680m^3 for the second variant) and a heavier structural mass. Groups 2 and 6 have identical weights on both variants due to the identical crew size (see Appendix 9.1) and payload, Table 5.8. Group 4 has a larger weight in the first variant due to additional equipment which was incorporated in that design to take advantage of the split move functional group (Figure 5.54). The weight (and space) relationships of groups 3 and 5 given in (UCL 2010b) are largely proportional to the ships volume and, therefore, are slightly heavier in the first AOR variant. Finally the differences in the group 8 weights, which refer to growth and board margins, are due to the fact that these margin types scale with lightships weight.

A9.3 Margin Philosophy

This appendix describes the margin philosophy adopted for the ship design studies developed. A brief discussion on margins in ship design is included in Appendix 1.

Frigate Variants (Including Baseline)

Table A15: Design and Construction Margins for Frigate Variant 1

	Weight (%)	**Space (%)**
1 hull	5	0
2 personnel	0	5
3 ship systems	5	2
4 main propulsion	5	0
5 electric power	5	0
6 payload	7	10
7 variable	5	4

The figures above are almost identical to the ones proposed in the UCL Ship Design Procedure (UCL 2010a), the only difference being that groups 4 and 5 were given identical percentage margin. This is because it was decided to adopt IFEP for the frigate design studies, therefore, causing an ambiguity in the boundary between these two weight groups. The selection of the above margin philosophy is relatively conservative, given that there were not any new major equipment or any major novel and unconventional features included in this design.

A similar principle was followed for the board and growth margins. A board margin of 2% (of lightships weight, amidships at No 1 Deck) and a growth margin of 5%, 0.5% per year for 10 years, (of lightships weight, at lightships centroid) were used, as indicated by the UCL Ship Design Procedure (UCL 2010a) for a typical combatant.

Identical board and growth margins, as well as design and construction margins to those adopted for the baseline frigate design (Table A15) were used during the design of Frigate Variants 2 and 3, with the only exception being the group 1 weight margin. This margin was doubled from 5% to 10% since Frigate Variants 2 and 3 incorporated unconventional features in their structural design. Frigate Variant 2 included a much smaller superstructure proportion that current conventional frigate type ships. Since generally superstructure weight is proportionately smaller than hull weight, and the relationship used for structural weight estimation (Equation 11) scales with ship gross volume, uncertainties were raised in the structural weight estimation of Frigate Variant 2, therefore, leading to the increase in the group 1 weight margin. In addition, since Equation 11 was derived using existing monohull ship data more speculation was raised regarding the validity of the application of that equation to multihull ships, such as Frigate Variant 3. However, since a trimaran is essentially a long narrow monohull (with the addition of two small side hulls connected by a box structure (Andrews and Hall 1995; Andrews 2004)), therefore, not entirely departing from the design principles of monohulls, it was decided to utilise the same structural weight relationship, by applying a larger (double) weight margin. The remaining margins were identical to the ones used for the baseline design since unconventionalities were not introduced in any other aspects of the designs.

Corvette and Destroyer

The board, growth and design and construction margins used for the Corvette and Destroyer design studies were identical to those used for the baseline frigate. This is because all three combatants are typical monohull modern combatants of their specific type, without any particular novel features being considered (possibly with the exception of IFEP, which was incorporated in all combatants, for consistency).

AOR Variants

Table A16: Design and Construction Margins for AOR Designs

	Weight (%)	Space (%)
1 hull	5	3
2 personnel	0	5
3 ship systems	7	3
4 main propulsion	8	4
5 electric power	8	4
6 payload	4	3
7 variable	7	4

Identical design and construction margins were applied to both replenishment ship designs as they are both equally conventional. Features worth mentioning are the overall larger space margins used for the AOR designs, when compared to the combatant designs due to the fact that replenishment ships are generally considered to be volume limited (Gale 2003), as identified in Appendix 2.3. The payload related margins are considerably smaller than the equivalent combatant margins due to the limited weapons and sensors incorporated in the AOR designs. On the other hand, the hull and variable margins are larger due to the large cargo (belonging to group 7) and specialised RAS equipment (belonging to group 1) present in the AORs. Since, similarly to the combatant design studies, an IFEP system was also selected for the replenishment ship designs, identical group 4 and 5 margins were applied. However, the incorporation of a relatively unconventional podded drive arrangement (see Section 5.3) led to a significant increase in these margins, compared to the combatant designs. Finally, group 3 margins are also increased due to the increasing complexity of ship systems and system distribution with ship size.

A board margin of 1% (of lightships weight, amidships at No 1 Deck) and a growth margin of 5%, 0.5% per year for 10 years, (of lightships weight, at lightships centroid) was used for both AOR designs. The UCL Ship Design Procedure (UCL 2010a) suggests a 2% board margin, for a typical combatant, as was used for the combatant design studies. However, for the AOR ship designs this value was halved as the board margin mainly refers to future weapon and sensor additions (Appendix 1), not as relevant to auxiliary ships.

A9.4 Powering Requirements

This appendix discusses the powering requirements of the ship design studies developed.

Frigate Variants (Including Baseline)

The hull effective power for Frigate Variant 1 was calculated through the Holtrop & Mennen method, which computes the naked hull effective power using data from the regression analysis of random model & full scale data (Holtrop 1984), and is advisable for combatants (QinetiQ 2011a). After taking into account air resistance, appendages, fouling (temperate, 180 days out of dock), hull roughness, and selecting two Wageningen B Series propellers (4.6m diameter, 5 blades), the following results were obtained. (Note that Holtrop & Mennen hull/propeller interaction method should be and was used in conjunction with the Holtrop & Mennen resistance method mentioned above).

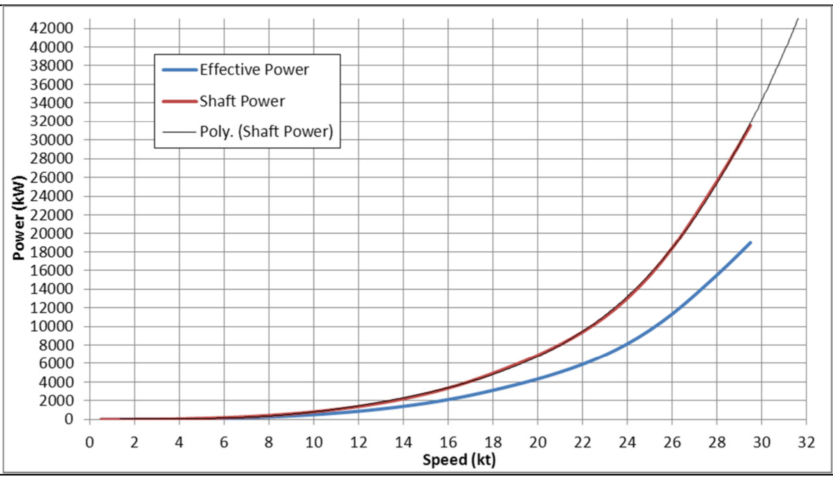


Figure A75: Frigate Variant 1 Power Speed Curve

A forecasting 6th order polynomial trendline is fitted in the power speed curve as the Holtrop & Mennen method could only operate until 29.5kts, whereas the requirement was for a maximum speed of 30kts (Table 5.2). It follows the power required for the propulsion system is approximately 34.5MW. The required hotel load was based on that of a similar UCL frigate design project (UCL 2006a), and was equal to 2.4MW, which should be duplicated. Therefore, (given that an IFEP system was selected for the frigate design), the total power generation requirement was 39.3MW. The machinery was then selected from references such as (Rolls-Royce 2002; UCL 2010b; Wartsila 2010), and consisted of:-

- 2 × 2.94MW Wartsila 9L26 diesel gensets (cruise);
- 1 × 31MW Rolls-Royce MT30 marine gas turbine, electrical drive (boost);
- 2 × 2.69MW Wartsila 16V200 diesel gensets (auxiliary).

The above machinery driving two FPPs on 20MW HTS motors (American Superconductor 2011). Thus, the total generated power was equal to 42.26MW, 36.88MW for propulsion, therefore meeting the 30kt requirement (30.5kts achieved), and 5.38MW for hotel load. It is clear that, due to the flexible IFEP arrangement, an even larger proportion of the generated power could be used for propulsion purposes, therefore, achieving even higher speeds. One of the two cruise engines is sufficient to propel the ship at its 15kt cruise speed, while all three cruise and boost engines are required to achieve the maximum speed.

The propulsive powering requirements for Frigate Variant 2 were computed in an identical manner as for Frigate Variant 1, producing the results shown in Figure A76.

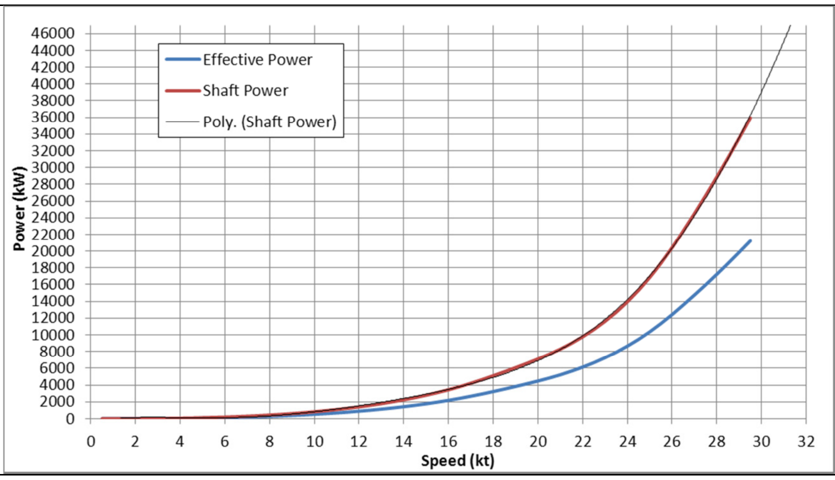


Figure A76: Frigate Variant 2 Power Speed Curve

The propulsion power required to propel the frigate at the maximum required speed of 30kts is approximately 39.5MW. This value is 5MW over the power required for the baseline frigate variant, due to the fact that, although both ships have the same beam, Frigate Variant 2 is shorter, heavier and has a deeper draught. The required hotel load was assumed to be constant for all frigates, at 2.4MW, which should be duplicated. Given that an IFEP system was used in order to remain consistent with the baseline variant, the total power generation requirement was equal to 44.3MW. The machinery selected consisted of (Rolls-Royce 2002; UCL 2010b; Wartsila 2010):-

- 2 × 5.22MW Wartsila 16V26 diesel gensets (cruise);
- 1 × 31MW Rolls-Royce MT30 marine gas turbine, electrical drive (boost);
- 2 × 2.69MW Wartsila 16V200 diesel gensets (auxiliary).

The above machinery driving two FPPs on 21MW HTS motors (American Superconductor 2011). The total generated power is equal to 46.82MW, 41.44MW for propulsion and 5.38MW for hotel load, and the maximum speed achieved is 30.4kts. One of the two Wartsila 16V26 cruise engines is sufficient to propel the ship at its 15kt cruise speed, while all three cruise and boost engines are required to achieve the maximum speed.

Since Paramarine did not contain a suitable powering model for trimaran hullforms, a UCL developed program, based on the Holtrop & Mennen method, was used for its powering estimations. This program allowed a 10% margin for interference effects between the three hulls, another 10% margin for appendage allowance and a propulsive coefficient of 0.65. The resultant power speed curve is shown in Figure A77.

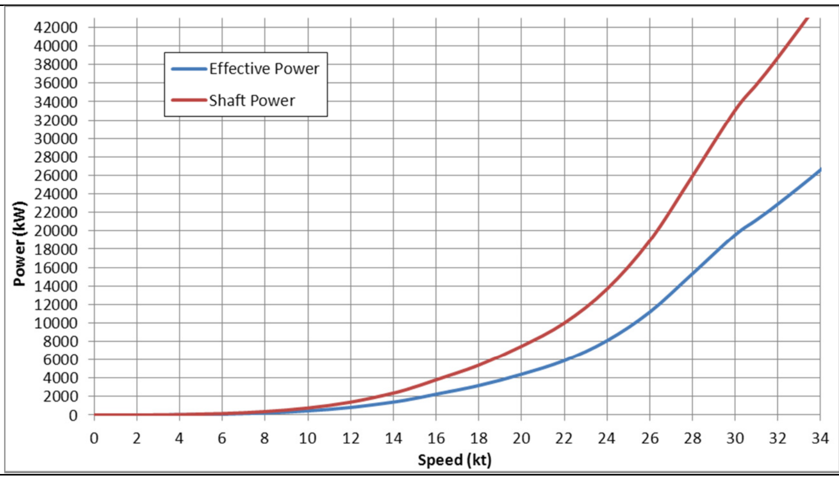


Figure A77: Frigate Variant 3 Power Speed Curve

The power requirement for the propulsion system (to attain the 30kt maximum required speed) is just under 34MW, i.e. the lowest between all variants, although the trimaran is the ship with the largest displacement. As in the two previous frigate design variants, a hotel load of 2.4MW, which should be duplicated, was assumed. Once again, an IFEP system was implemented, for consistence between the three variants, leading to a total power generation requirement of 38.8MW. Since this value was just 0.5MW less than the one for the baseline frigate, it was decided that both ships would contain the same engines, i.e. (Rolls-Royce 2002; UCL 2010b; Wartsila 2010):-

- 2 × 2.94MW Warstila 9L26 diesel gensets (cruise);
- 1 × 31MW Rolls-Royce MT30 marine gas turbine, electrical drive (boost);
- 2 × 2.69MW Wartsila 16V200 diesel gensets (auxiliary).

The above machinery driving a single (4.6m diameter, 5 blades) FPP on a 37MW HTS motor (American Superconductor 2011) and a single Schottel SPJ 520 Pump-Jet (Schottel 2010b) on a 3.5MW HTS motor. The total generated power of Frigate Variant 3 is equal to 42.26MW, 36.88MW for propulsion and 5.38MW for hotel load, identically to the baseline design. The maximum achieved speed was 31.3kts (although speeds in excess of 32kts could be reached due to the flexible IFEP system), making it the faster, although heavier, of the three variants. Conversely, Frigate Variant 2, although generating more power than the other two variants, had the least top speed. This clearly demonstrates the advantages trimarans encompass when considering high speed craft. However, when considering the propulsion power required at the cruise speed (15kts), Frigate Variant 3 is the least efficient requiring 3,040kW of shaft power, in contrast to 2,740kW and 2,790kW required by Frigate Variants 1 and 2. The above also implies that the trimaran frigate was the only variant to require both cruise engines in order to achieve its cruise speed. However, only one cruise engine and the boost engine are sufficient to achieve the maximum required speed of 30kts. It is of interest to note that the cruise speed of Frigate Variant 3 could be reached with the pump-jet alone, as could the maximum speed with the propeller alone.

Corvette and Destroyer

The propulsive power requirements for the Corvette were estimated (through the inbuilt Paramarine powering module) by using the Holtrop & Mennen method for hull effective power, as for Frigate Variants 1 and 2, due to its satisfactory applicability for smaller naval vessels (QinetiQ 2011a). Air resistance, appendages, fouling (temperate, 180 days out of dock), and hull roughness were accounted for; one Wageningen B Series propeller (3.4m diameter, 5 blades) was selected and the Holtrop & Mennen hull/propeller interaction method was used in order to obtained the power speed curve depicted in Figure A78.

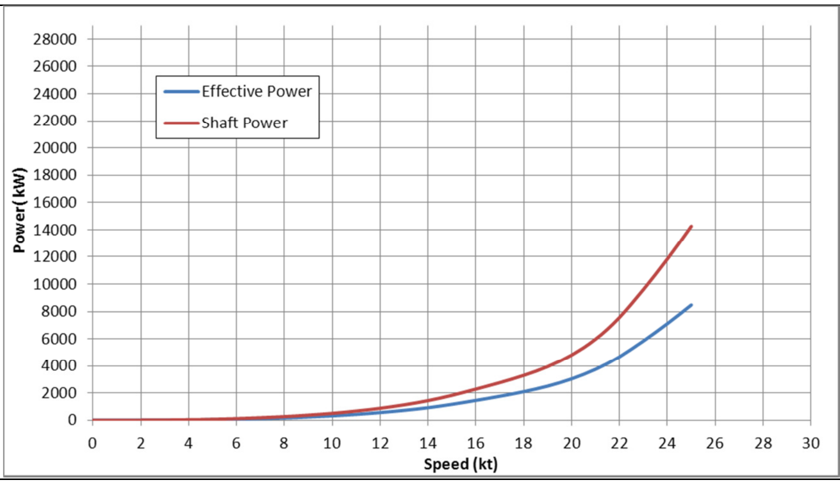


Figure A78: Corvette Power Speed Curve (Low Speeds)

The limiting maximum speed value for the Holtrop & Mennen method in conjunction with the Corvettes hull was only 25kts. It was considered unsatisfactory to fit a forecasting (to the required maximum speed of 30kts, Table 5.5) polynomial to the above curve (as was done for Frigate Variants 1 and 2) due to the large uncertainties involved. It was therefore, decided to use the above results for low speed calculations (e.g. cruise speed endurance estimations). The Holtrop & Mennen method for hull effective power estimation was substituted by the Fung 2 method (Fung and Leibman 1995) for power estimations at higher speeds. This method computes effective power using regression equations for high speed transom sterns (Fung and Leibman 1995). The output power speed curve is shown in Figure A79.

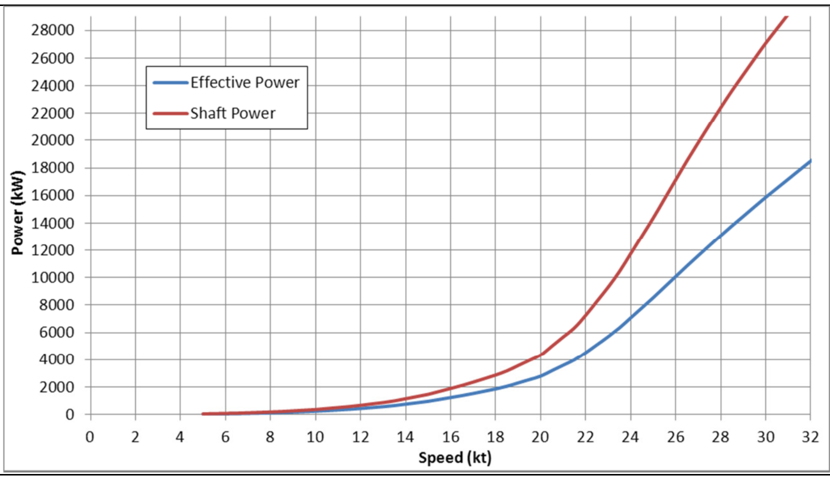


Figure A79: Corvette Power Speed Curve (High Speeds)

From above, the propulsive power required to achieve the 30kt requirement was approximately 27MW, 7.5MW less than the (considerably larger) baseline frigate. The required hotel load was based on that similar UCL designed Corvettes and was equal to 1.2MW, which should be duplicated (i.e. half of that of Frigate Variant 1). An IFEP system was selected to avoid inconsistencies; therefore, the total power generation requirement was approximately 29.4MW. The machinery was then selected from references such as (UCL 2010b; Wartsila 2010; GE Marine 2012), and consisted of:

- 2 × 1.2MW Warstila 6L20 diesel gensets (cruise);
- 1 × 24.05MW General Electric LM2500 marine gas turbine, electrical drive (boost);
- 2 × 1.2MW Wartsila 6L20 diesel gensets (auxiliary).

The above machinery driving a single a single FPP propeller on a 25.5MW HTS motor (American Superconductor 2011) and a single Schottel SPJ 220 Pump-Jet (Schottel 2010b) on a 1MW HTS motor. The total generated power of the Corvette is equal to 28.85MW, 26.45MW for propulsion and 2.4MW for hotel load, and the maximum speed achieved was 29.7kts. Both cruise engines are required to propel the ship at its cruise speed, while all boost and cruise engines are required for the maximum speed. The Corvette can attain a speed of just over 12kts with the pump-jet alone and just over 29kts with the propeller alone.

The propulsive powering requirements for the Destroyer were computed in an identical manner as for Frigate Variants 1 and 2, the only difference being the selection of a two 5 blade Wageningen B Series propellers, 5m in diameter.

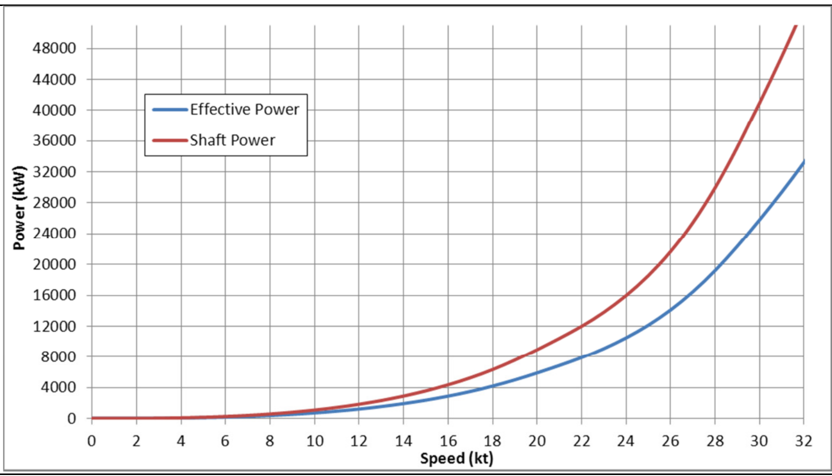


Figure A80: Destroyer Power Speed Curve

From Figure A80, it arises that a propulsive power of approximately 40MW is required to achieve the 30kt requirement, 5.5MW more than the baseline frigate. The required hotel load was again based on that similar UCL ships design studies and was equal to 4.8MW, which should be duplicated (i.e. double that of Frigate Variant 1). Given that an IFEP system was used in order to remain consistent, the total power generation requirement was equal to approximately 49.6MW. The machinery selected consisted of (Rolls-Royce 2002; UCL 2010b; Wartsila 2010):-

- 2 × 4.08MW Wartsila 12V26 diesel gensets (cruise);
- 1 × 31MW Rolls-Royce MT30 marine gas turbine, electrical drive (boost);
- 2 × 5.22MW Wartsila 16V26 diesel gensets (auxiliary).

The above machinery driving two FPPs on 21MW HTS motors (American Superconductor 2011). The total generated power is therefore 49.6MW, 39.16MW for propulsion and 10.44MW for hotel load. The maximum speed attained is 29.7kts. One of the two Wartsila 12V26 cruise engines is sufficient to propel the ship at its 15kt cruise speed, while all cruise and boost engines are required to achieve the maximum speed.

AOR Variants

In order to calculate hull effective power for the AOR Variants, the Andersen method (Andersen and Guldhammer 1986) was utilised. This method is suitable for low, medium and high speed merchantmen including a bulbous bow (QinetiQ 2011a). Air resistance, appendages, fouling (temperate, 180 days out of dock) and hull roughness were included in order to compute the effective power. Since the powering method of Paramarine does not include a hull/pod interaction option, it was decided to simply assume a propulsive coefficient of 0.65. The resulting power against speed curve for AOR Variant 1 is shown in Figure A81.

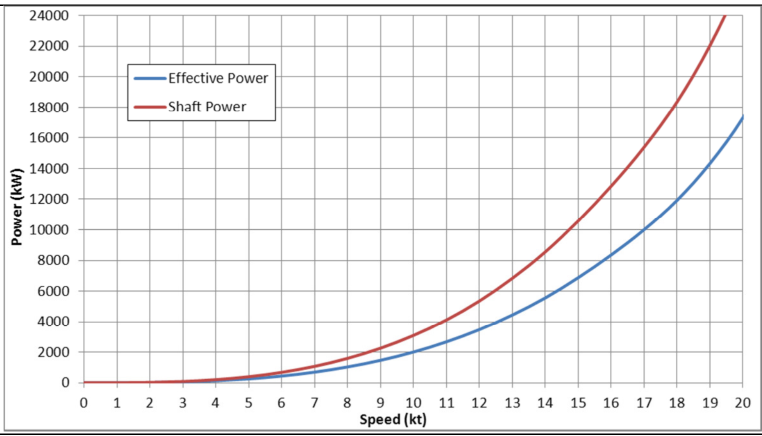


Figure A81: AOR Variant 1 Power Speed Curve

In order to achieve the 18kt maximum speed requirement (Table 5.7) the propulsive power required is approximately 18.5MW. The required hotel load was again based on work done by Martin (2001), and was equal to 2.2MW, which should be duplicated. Therefore, given the selected IFEP system, the total power generation requirement was 22.9MW. The following machinery was selected (UCL 2010b; Wartsila 2010):

- 4 × 5.76MW Wartsila 12V32 diesel gensets (cruise and auxiliary);
- 1 × 0.685MW Wartsila 4L20 diesel genset (emergency).

Note that, unlike in the combatant design studies, the AOR designs did not include dedicated propulsion and auxiliary engines, due to the less demanding power requirements of such ships. The machinery above drove two stern mounted SSP10 10MW pods (Geertsma 1999; UCL 2010b) and one Schottel SPJ 220 Pump-Jet (Schottel 2010b) on a 1MW HTS motor (American Superconductor 2011). The total generated power is equal to 23.725MW and, given that the required generation for the hotel load was 4.4MW, the remaining 19.325MW was used for propulsion, achieving a maximum speed of 18.3kts. However, marginally higher speeds can be achieved due to the flexible IFEP arrangement. For example, 18.4kts can be achieved on the pods alone, 7kts on the pump-jet alone and 18.7 on all three propulsors. The required cruise speed of 15kts can be reached with two of the Wartsila 12V32 diesel gensets, while the 18kt required maximum speed is achieved with all main engines operating.

In order to calculate the powering requirements of AOR Variant 2, the identical procedure to that for AOR Variant 1 was followed. The resulting power against speed curve is shown in Figure A82.

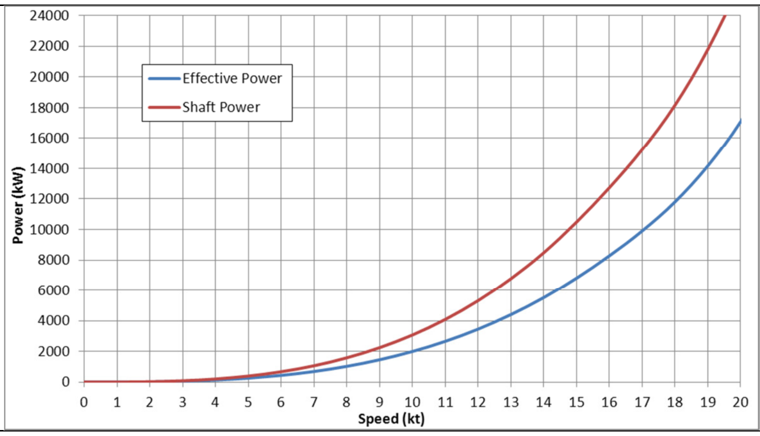


Figure A82: AOR Variant 2 Power Speed Curve

Just over 18MW are required in order to achieve the required maximum speed of 18kts. This value is slightly lower than the equivalent power value of AOR Variant 1 due to its marginally lower displacement and, therefore, draught, since the same hull was used for both designs. It was assumed that the hotel load for both AOR design variants was invariable (2.2MW, which should be duplicated (Martin 2001)). The total power generation requirement, for an IEFP system, was approximately 22.6MW. Since this value was almost identical to that of the first AOR variant, the machinery selected for both designs was also identical (UCL 2010b; Wartsila 2010):

- 4 × 5.76MW Wartsila 12V32 diesel gensets (cruise and auxiliary);
- 1 × 0.685MW Wartsila 4L20 diesel genset (emergency).

The above machinery driving two stern mounted SSP10 10MW pods (Geertsma 1999; UCL 2010b). As with AOR Variant 1, 19.325MW of the total 23.725MW generated power was directed to propulsion, attaining a maximum speed of 18.3kts, therefore, complying with the maximum speed requirement. Alike the first AOR variant, the 15kt cruise speed can be reached with two of the Wartsila 12V32 diesel gensets, while the maximum speed is achieved with all main engines operating.

A9.5 Hydrostatics Analysis

This appendix reviews the hydrostatics analysis of the ship design studies developed.

Frigate Variants (Including Baseline)

Stability analysis was conducted for two conditions, deep and light, the light condition being equal to the deep minus all variable loads. Variable loads include all liquid tanks (lube oil, dieso, AVCAT and water) 86% full (to cover lack of pumpability, tanks not being fully pressed and the volume consumed in the tanks by structure, given a factor of 0.95 in each case as suggested by (UCL 2010b)), all magazines full to capacity, all provision stores (beer, NAAFI, frozen provisions, fresh provisions, dry provisions and clothing and mess gear) full to capacity and the helicopter.

Intact stability was assessed against Defence Standard 02-109 (NES 109) Stability Standards for Surface Ships (MOD 2000) until all criteria were passed. The figures and tables below show the GZ curves and the hydrostatic results outputted by Paramarine, for the deep and light conditions, for all three frigate Variants.

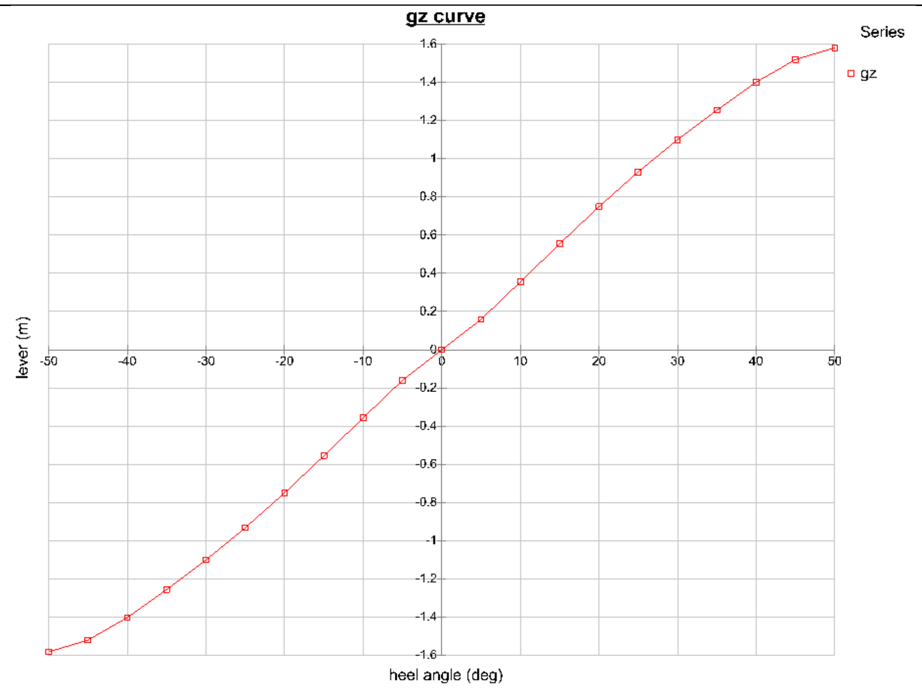


Figure A83: Frigate Variant 1 Deep Condition GZ Curve

Table A17: Frigate Variant 1 Deep Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.606	4.022	4.325	3.719	0.022	3,888.179
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-5.781	-0.001	5.642	-5.8	-0.002	2.502
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-7.428	-0.001	1,482.159	8.12	351.769	1.222
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
37.044	2.478	346.127	1.256	309.083	101.847

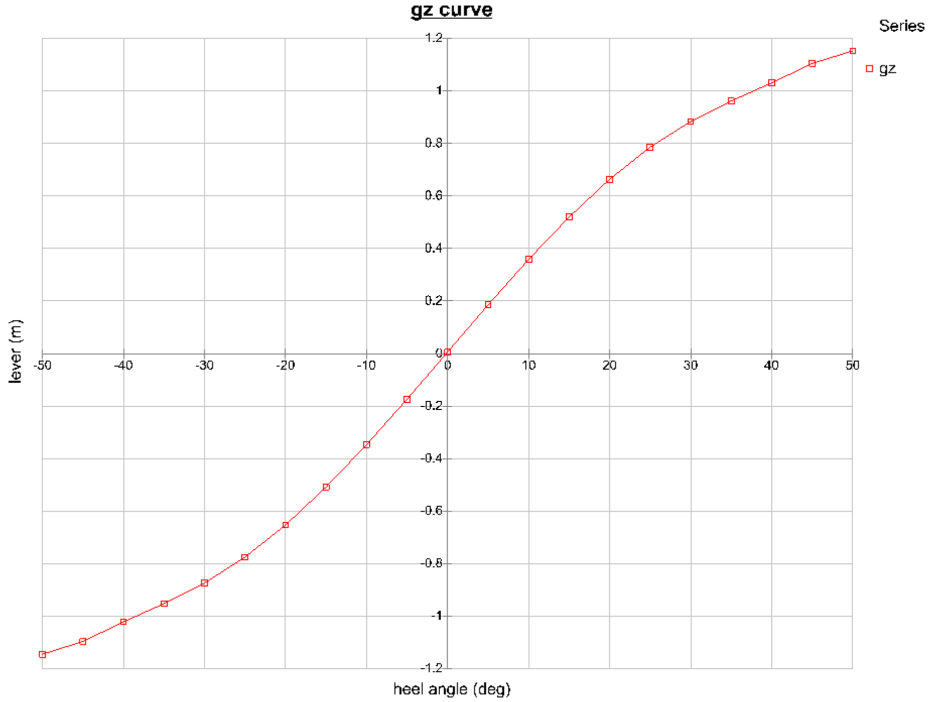


Figure A84: Frigate Variant 1 Light Condition GZ Curve

Table A18: Frigate Variant 1 Light Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.843	3.579	4	3.157	-0.158	3,268.62
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-6.246	0.006	6.338	-6.279	0.017	2.25
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-7.635	0.009	1,426.226	8.408	389.059	0
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0	2.069	382.721	2.069	382.721	106.017

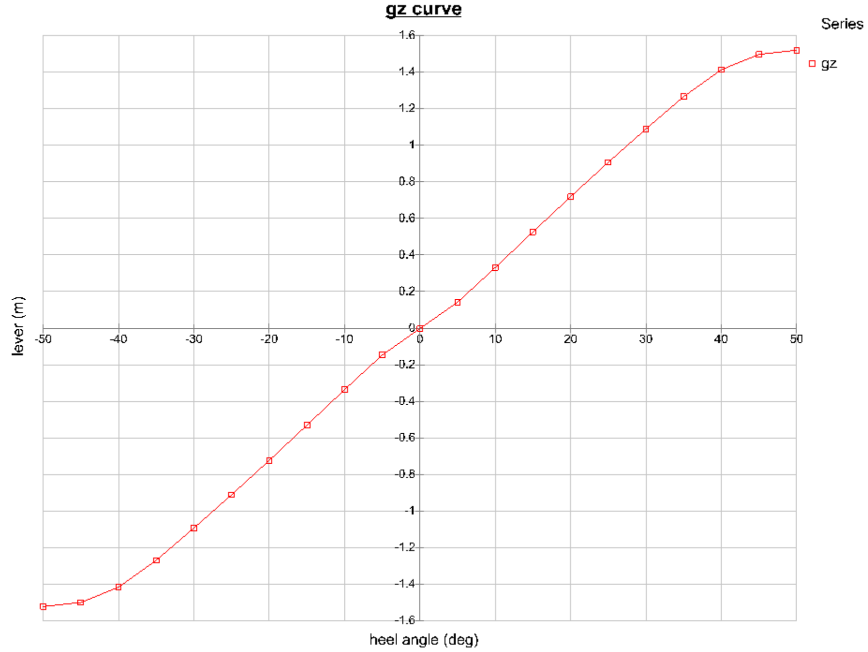


Figure A85: Frigate Variant 2 Deep Condition GZ Curve

Table A19: Frigate Variant 2 Deep Condition Hydrostatics

Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.414	4.441	4.648	4.234	0.088	4,063.193
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-5.067	-0.005	5.695	-5.071	-0.008	2.755
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-7.639	-0.004	1,422.113	8.058	291.527	1.357
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
45.366	2.362	285.832	1.005	240.466	82.803

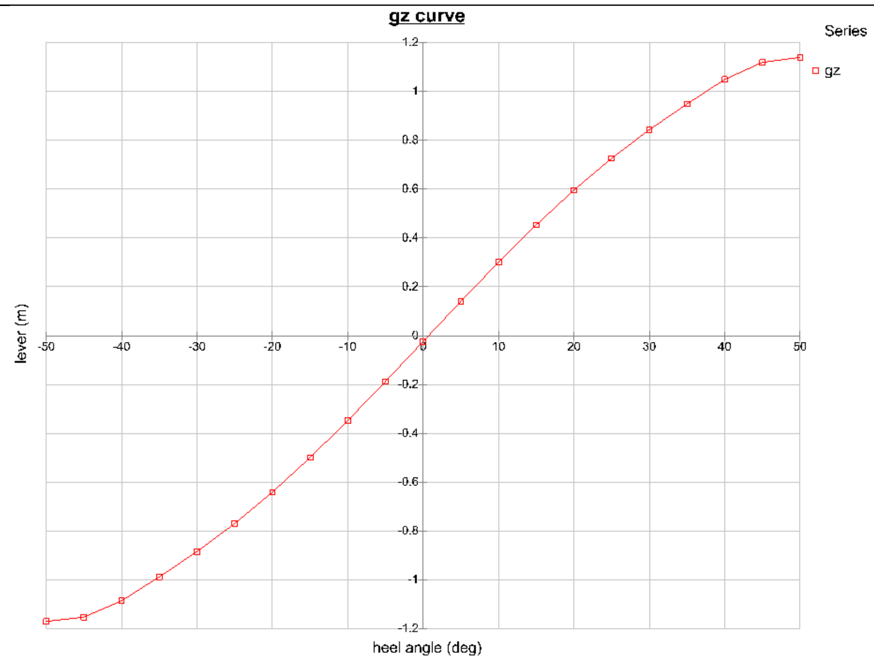


Figure A86: Frigate Variant 2 Light Condition GZ Curve

Table A20: Frigate Variant 2 Light Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.384	4.003	4.196	3.811	0.73	3,449.566
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-4.547	-0.024	6.328	-4.554	-0.073	2.489
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-7.354	-0.04	1,367.943	8.218	318.802	0
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0	1.89	312.474	1.89	312.474	91.349

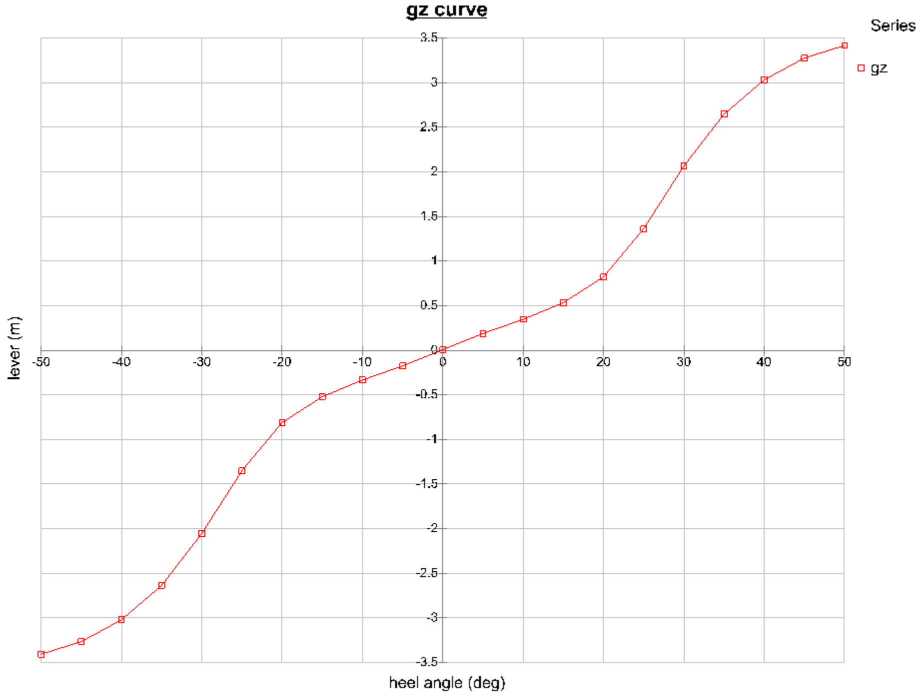


Figure A87: Frigate Variant 3 Deep Condition GZ Curve

Table A21: Frigate Variant 3 Deep Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.619	5.186	5.496	4.877	-0.163	4,334.764
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-4.357	0.008	6.854	-4.37	0.018	3.267
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-11.127	0.018	1,375.078	9.399	401.928	0.496
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
26.975	2.545	395.074	2.049	368.1	110.045

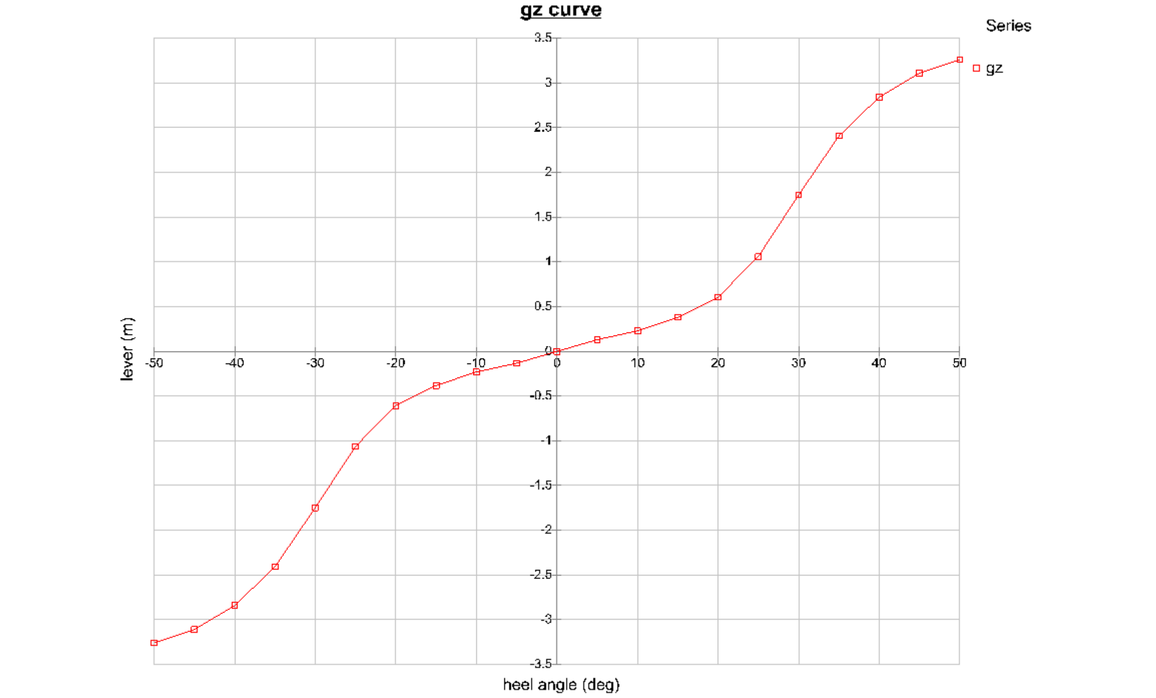


Figure A88: Frigate Variant 3 Light Condition GZ Curve

Table A22: Frigate Variant 3 Light Condition Hydrostatics

Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.893	4.787	5.234	4.341	0.061	3,816.225
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-4.269	-0.001	7.511	-4.295	-0.006	3.031
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-11.071	-0.007	1,332.209	9.158	438.241	0.02
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0.106	1.647	430.73	1.627	430.624	113.337

From above, the major difference between the trimaran and the monohull frigate variants is that, for the trimaran, a GMt of 2m in the deep condition was pursued (in contrast to the typical values of 1m – 1.5m for monohull combatants (Usher and Dorey 1982)). The higher GMt was aimed at giving an acceptable rolling response in beam seas, since trimarans have inherently greater roll inertia than monohulls (Andrews and Zhang 1995; Andrews 2004). In fact, the above two references even suggested that the required GMt could be as high as 2.5m; however, further research is necessary in the area of trimaran seakeeping. Another point of interest in the stability analysis of the trimaran frigate is that, unlike the other two variants, it required approximately 122te of ballast at the light condition. The ballast was placed in trim tanks located at the forward end of the frigate, in order to counter the excessive trim at the light condition. The excessive trim was caused mainly due to the midpoint of the side hulls and box structure being aft of amidships, and was managed by the location of the fuel tanks at the deep condition. Another implication is that the light displacement of Frigate Variant 3 is not equal to its variable load subtracted from the deep displacement (Table A10) since ballast also belongs to the variable group. The use of ballast (and, therefore, increased light displacement) of the trimaran would add to the disadvantages of this ship regarding the required power to propel it at the cruise speed. The trim tanks (in blue) and fuel tanks (in yellow) are clearly visible in Figure A89.

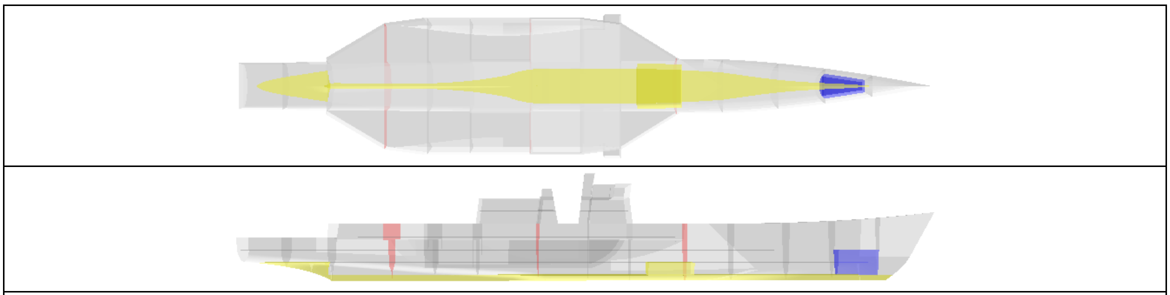


Figure A89: Frigate Variant 3 Fuel and Ballast tank Location

Damage stability (of both deep and light conditions) was assessed against Defence Standard 02-109 (NES 109) damage criteria assessment (MOD 2000). A brief summary of these criteria is given in Appendix 4.2 and Figure A30. According to (MOD 2000), the following degree of damage should be assumed when assessing damage stability for vessels of water line length greater than 92m designed to MOD standards with a military role: "Damage anywhere along its length, extending 15% of the waterline length, or 21m whichever is greater". For the first two frigate designs, 21m is greater; therefore, the following damage conditions were assessed until all criteria were passed. Note that the areas in yellow in the figures below represent the damaged/flooded sections of each ship design in each damage condition.

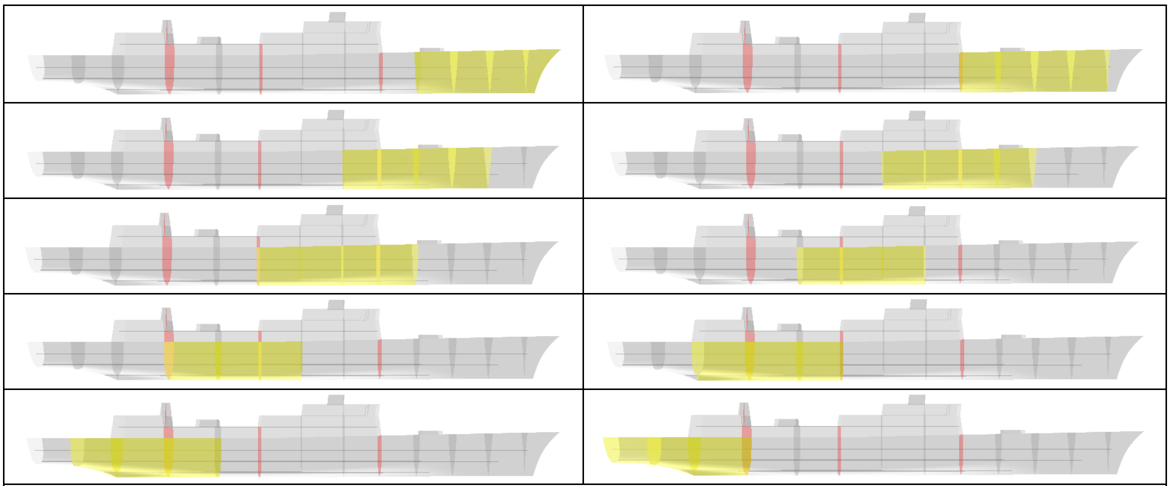


Figure A90: Frigate Variant 1 Damage Stability Assessment Cases

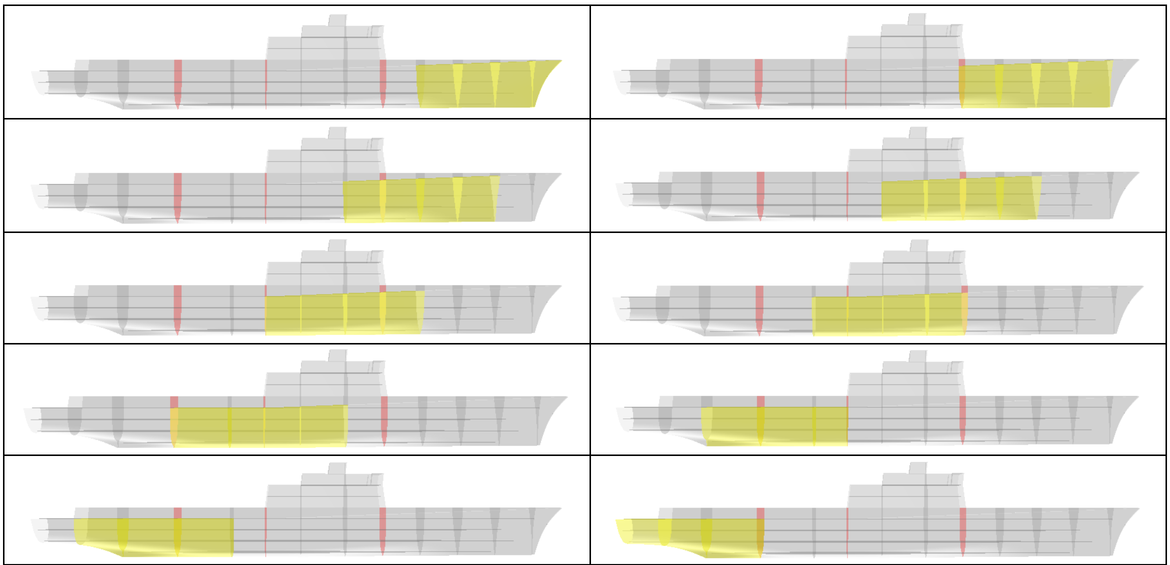


Figure A91: Frigate Variant 2 Damage Stability Assessment Cases

For the damage stability assessment of Frigate Variant 3, a damage length equal to 15% of the waterline length (i.e. approximately 21.6m) was assumed. In addition, flooding of both side hulls (separately, but in their entirety) was also evaluated. The damage cases shown in Figure A92 were examined.

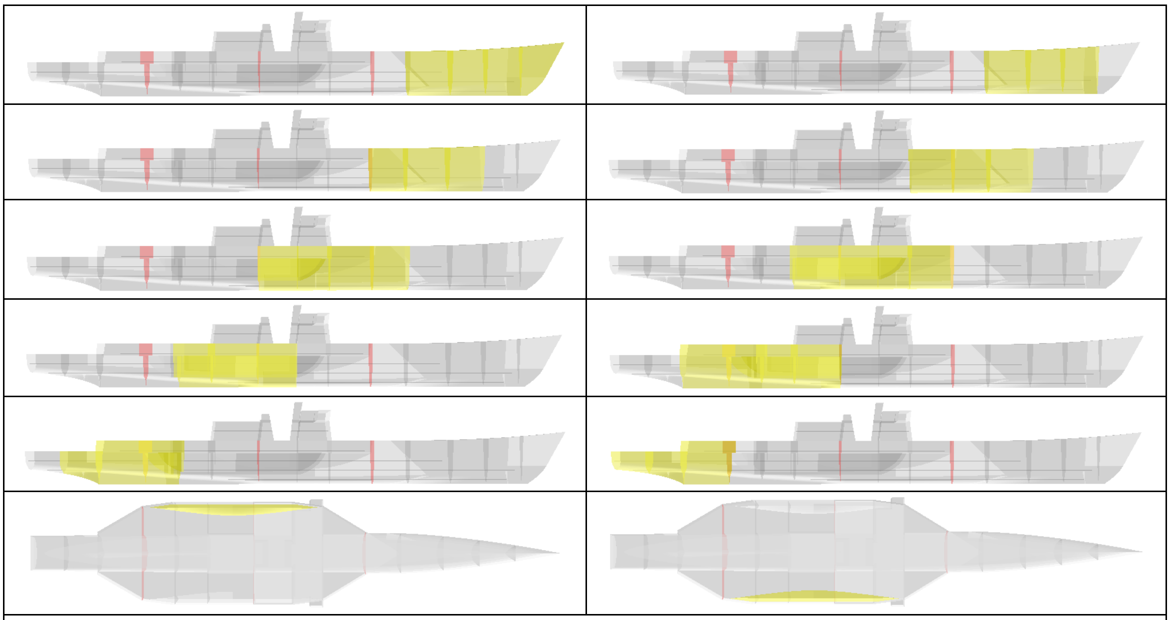


Figure A92: Frigate Variant 3 Damage Stability Assessment Cases

In order for Frigate Variant 3 to pass the asymmetric damage stability assessments, the undamaged hull had to be ballasted, therefore, justifying the decision of keeping the side hulls void in order to use as ballast tanks. In the port side hull damage case, 10% fullness of the starboard side hull in the deep condition and 35% fullness in the light condition were proved sufficient. In the case of damage to the starboard side hull, the port side hull had to be 35% full of ballast in both the deep and the light condition in order to pass the assessment.

Corvette and Destroyer

For the Corvette and Destroyer designs, stability analysis was conducted under the identical weight conditions as for the three frigate designs, summarised above. Intact stability was again assessed against Defence Standard 02-109 (NES 109) Stability Standards for Surface Ships (MOD 2000). The figures and tables below show the GZ curves and the hydrostatic results outputted by Paramarine, for the deep and light conditions, for the Corvette and Destroyer designs.

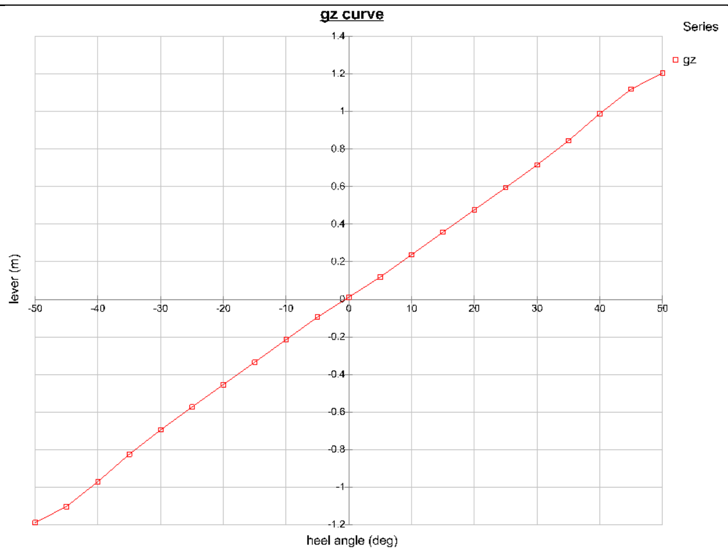


Figure A93: Corvette Deep Condition GZ Curve

Table A23: Corvette Deep Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.505	3.863	4.116	3.61	-0.587	1,832.549
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-4.519	0.016	5.149	-4.538	0.043	2.438
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-6.911	0.031	784.43	6.614	171.659	0.394
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
10.782	1.466	166.511	1.071	155.729	35.673

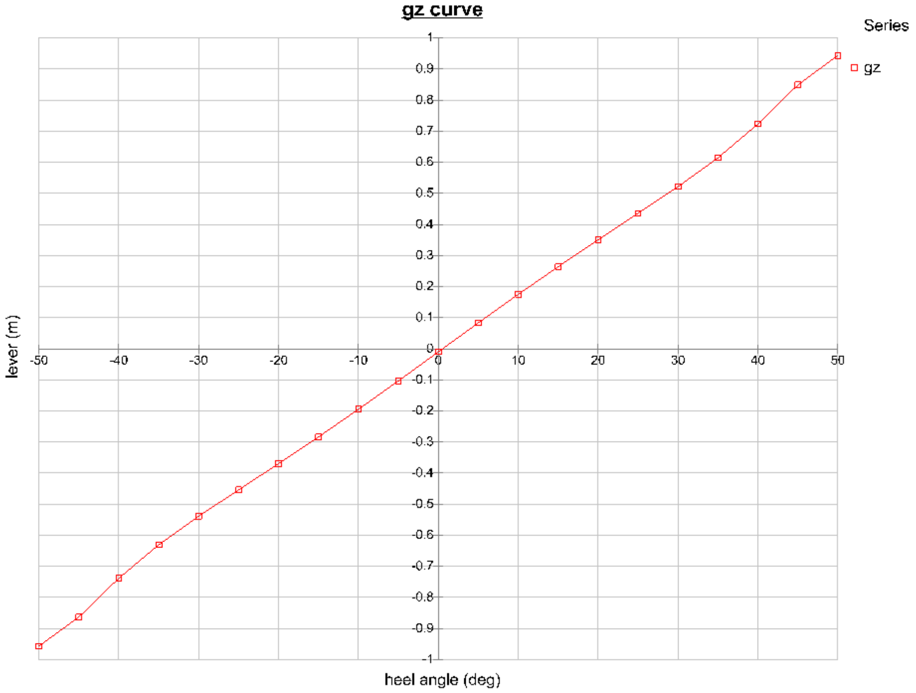


Figure A94: Corvette Light Condition GZ Curve

Table A24: Corvette Light Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.533	3.615	3.882	3.349	0.537	1,643.088
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-4.305	-0.01	5.509	-4.331	-0.04	2.283
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-6.833	-0.031	758.874	6.582	180.602	0
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0	1.073	175.093	1.073	175.093	35.963

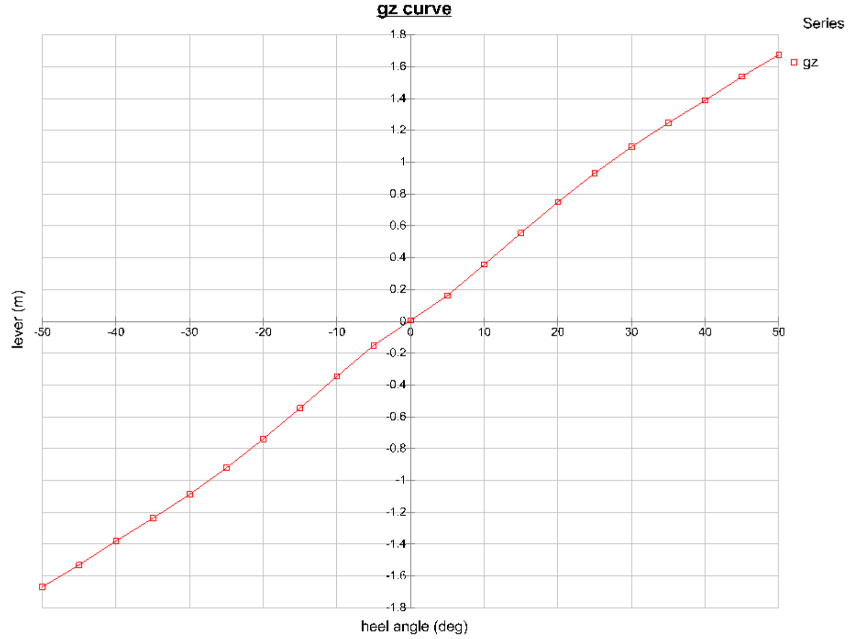


Figure A95: Destroyer Deep Condition GZ Curve

Table A25: Destroyer Deep Condition Hydrostatics

Trim BP (m)	Mean draught (m)	Draught AP (m)	Draught FP (m)	List or loll angle (deg)	Displacement (te)
0.644	4.745	5.067	4.423	-0.233	6,248.038
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-5.826	0.011	6.999	-5.846	0.027	2.944
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-8.151	0.013	2,035.618	9.48	415.605	1.252
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
36.063	2.481	408.606	1.229	372.542	166.262

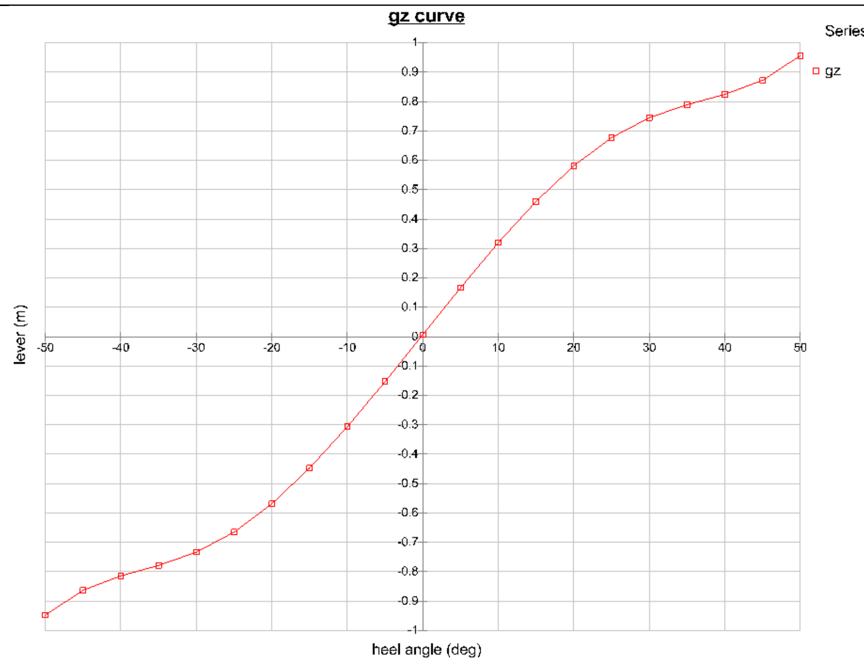


Figure A96: Destroyer Light Condition GZ Curve

Table A26: Destroyer Light Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.957	4.161	4.639	3.683	-0.21	5,121.255
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
-6.361	0.007	8.002	-6.399	0.026	2.607
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
-8.343	0.014	1,945.146	9.845	465.405	0
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0	1.843	457.404	1.843	457.404	167.322

The Destroyer design study was the only design to require longitudinal subdivision of (two of the three) dieso tanks above the double bottom (on No 5 Deck) in order to achieve a suitable fluid GMt in the deep condition. This was necessary due to the large amount of fuel needed to meet the demanding endurance requirement (Table 5.5). The two fuel tanks were subdivided into three (port, middle, starboard) smaller tanks, as illustrated in Figure A97, where all fuel tanks are shown in yellow.

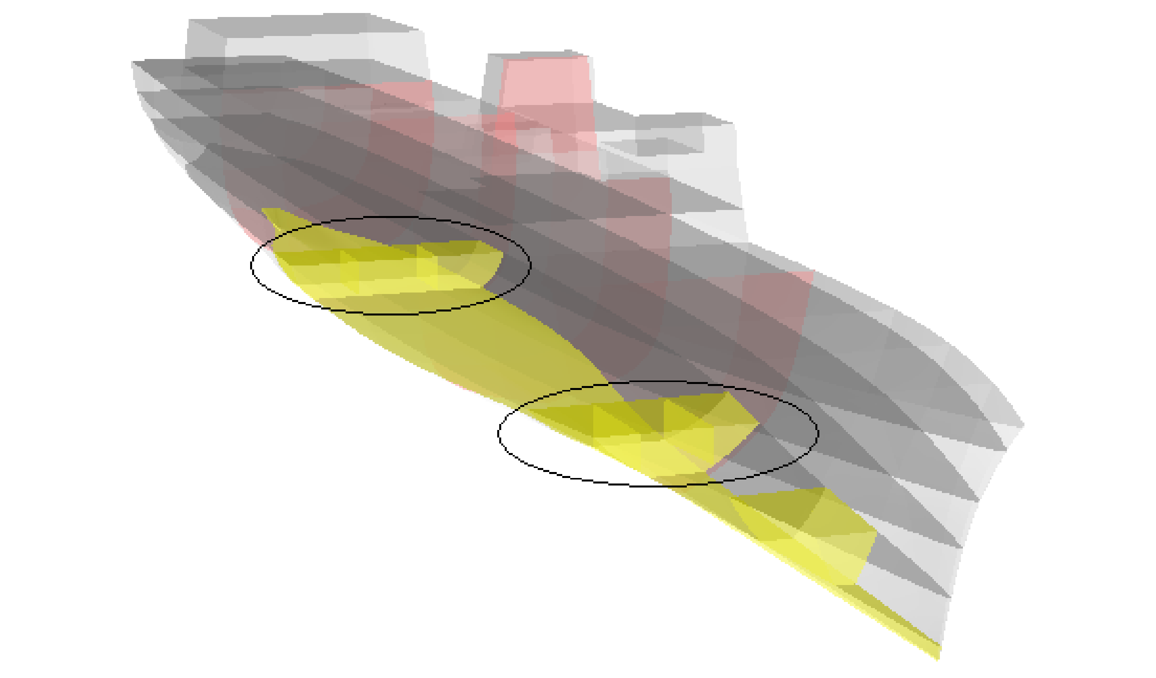


Figure A97: Destroyer Fuel Tank Arrangement

Although this arrangement produces satisfactory intact stability characteristics, it might cause large heel angles if one of the side tanks were flooded. This was observed with several Japanese and British WWII cruisers incorporating longitudinal bulkheads (Brown and Brown 1986) as mentioned in Appendix 4.2.

As for the frigate variants, damage stability (of both deep and light conditions) was assessed against Defence Standard 02-109 (NES 109) damage criteria assessment (MOD 2000). For vessels designed to MOD standards with a military role, of waterline length between 30m and 92m, such as the Corvette design, the following extent of damage should be assumed: “Any two adjacent main compartments. A ’main compartment’ is to have a minimum length of 6m”. Therefore, damage stability for the Corvette was assessed for the damage extents shown in Figure A98.

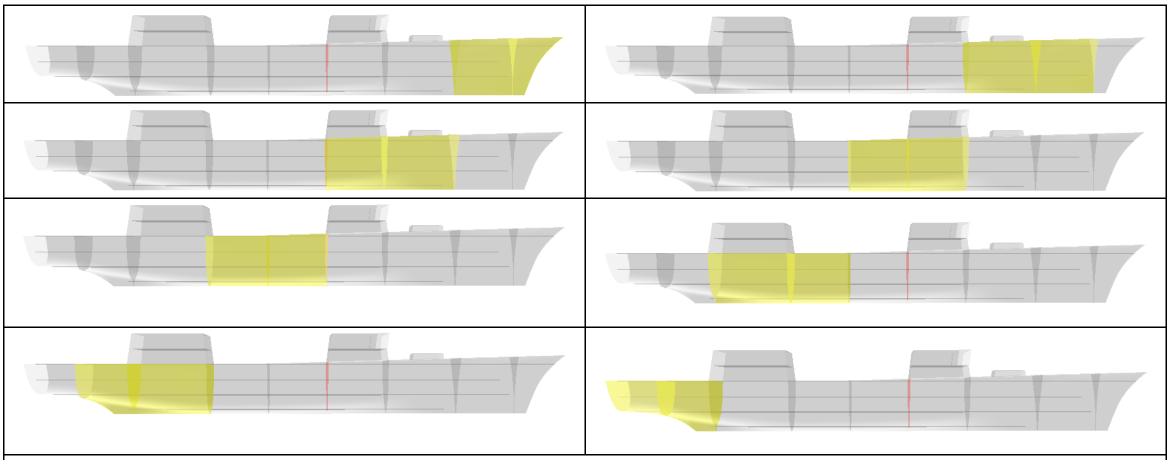


Figure A98: Corvette Damage Stability Assessment Cases

The problematic nature of current damage stability assessment criteria (outlined in Appendix 4.2) is highlighted, since the baseline frigate was assessed against the flooding of three or four adjacent WT sections (Figure A90), as opposed to two for the Corvette design, based purely on ship length without giving any considerations to other factors such as the threat to which the ship is assessed against.

Having a waterline length greater than 92m, damage stability assessment for the Destroyer was conducted assuming a damage length of 15% of the waterline length (i.e. approximately 22.1m). The damage extents shown in Figure A99 were assessed.

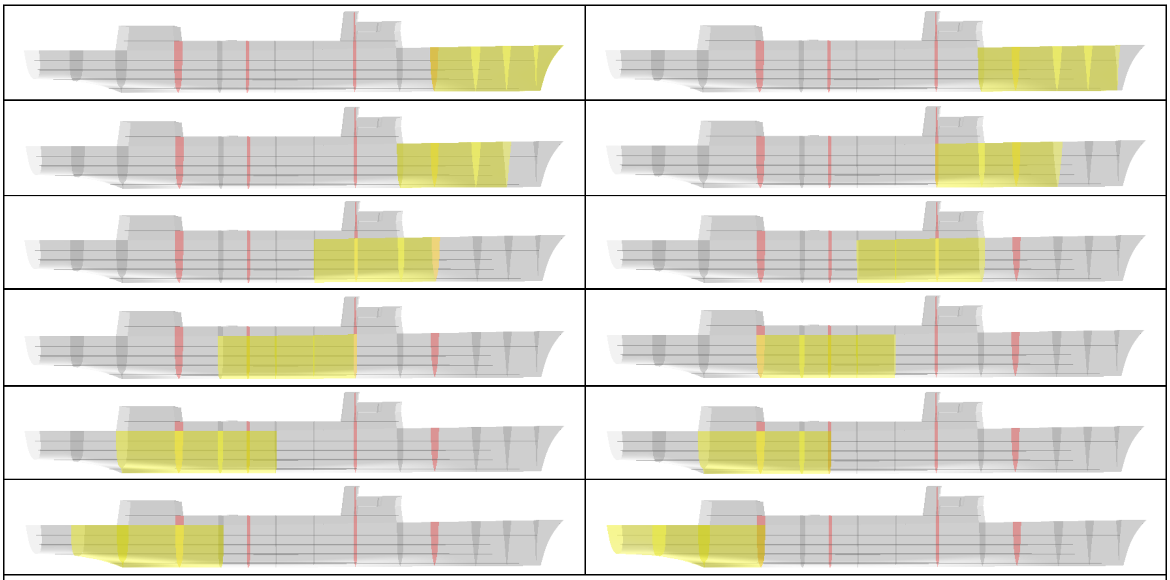


Figure A99: Destroyer Damage Stability Assessment Cases

AOR Variants

Stability analysis for the two AOR Variants was carried out for the deep and light conditions. The light condition is equal to the deep displacement, minus all variables (seawater side protection system for ordnance stores, ships own lube oil, dieso and AVCAT, magazines, helicopter, solid and liquid cargo, victualing and medical stores, beer, NAAFI, frozen provisions, fresh provisions, dry provisions, clothing and mess gear and ballast in the case of AOR Variant 2; 21,520te and 21,190te for the two variants respectively), plus any required, light condition, ballast and trim seawater (6,690te, 6,700te for the two variants respectively). It should be noted that all liquid tanks were assumed to be able to reach 95% fullness (rather than 86% in the combatant design studies) due to their much larger sizes.

Intact stability was assessed against both Defence Standard 02-109 (NES 109) Stability Standards for Surface Ships (MOD 2000) and the Code on Intact Stability for all Types of Ships Covered by IMO Instruments (IMO 1993), until all criteria were passed. The figures and tables below show the GZ curves and the hydrostatic results outputted by Paramarine, for the deep and light conditions, for both AOR Variants.

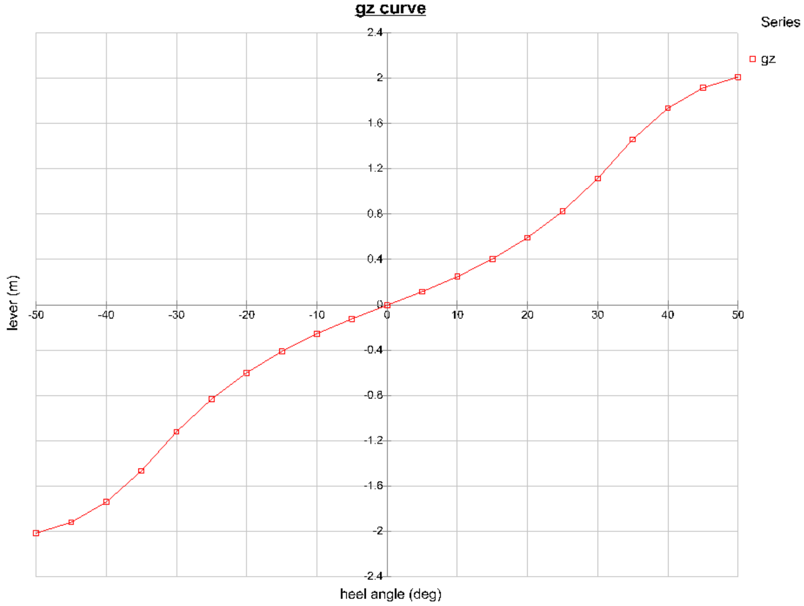


Figure A100: AOR Variant 1 Deep Condition GZ Curve

Table A27: AOR Variant 1 Deep Condition Hydrostatics

Trim BP (m)	Mean draught (m)	Draught AP (m)	Draught FP (m)	List or loll angle (deg)	Displacement (te)
0.726	12.014	12.377	11.651	0.179	38,453.3
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
98.853	-0.005	10.924	98.846	-0.017	7.064
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
92.197	-0.009	4,474.813	12.519	312.837	0.242
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0.479	1.595	301.913	1.353	301.434	585.412

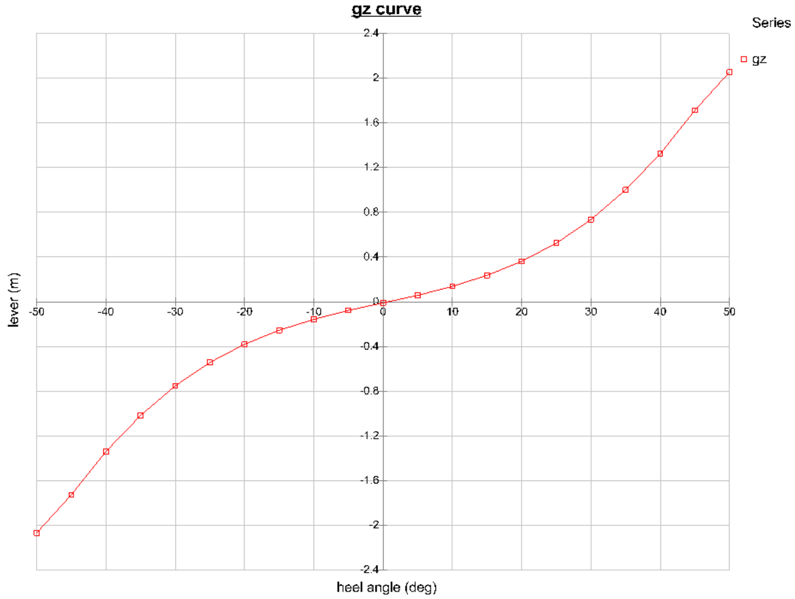


Figure A101: AOR Variant 1 Light Condition GZ Curve

Table A28: AOR Variant 1 Light Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
1.188	8.495	9.089	7.901	0.777	23,619.32
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
102.112	-0.012	10.992	102.083	-0.092	5.023
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
92.449	-0.051	3,971.481	11.817	404.542	0.124
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0.601	0.824	393.549	0.7	392.948	468.746

In the deep condition, no ballast was required for AOR Variant 1, although all liquid tanks were longitudinally subdivided into 3 smaller (port, centre and starboard) tanks, by two longitudinal bulkheads, to prevent lolling (GA, Appendix 8). In the light condition all ballast tanks (located between the double hulls as clearly visible in the GA, Appendix 8, and Figure A104) were full, as were the forward trim tanks. The total mass of trim water was 640te.

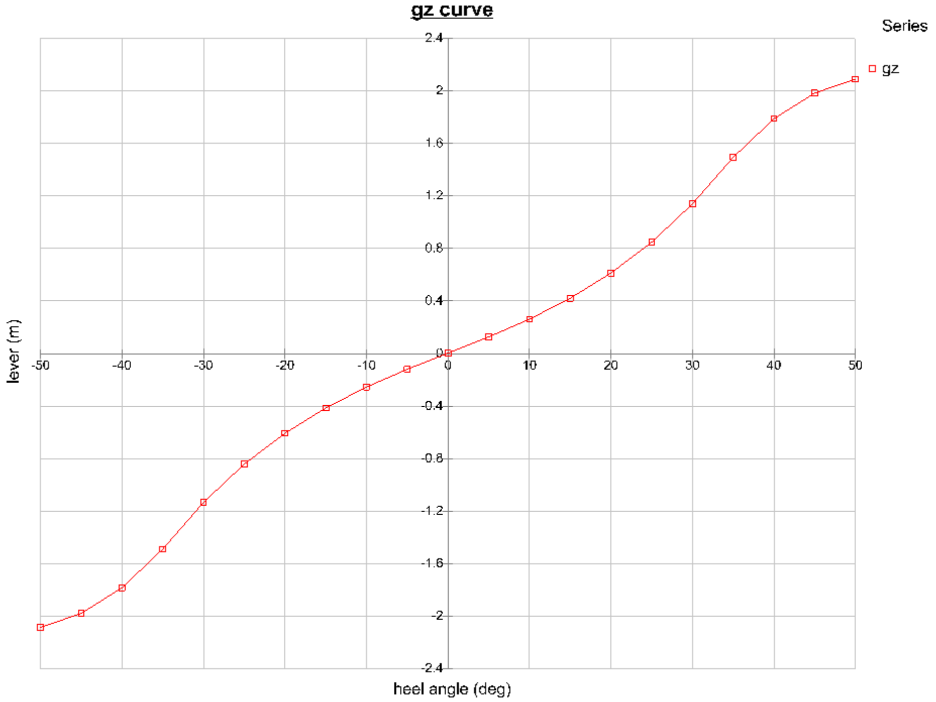


Figure A102: AOR Variant 2 Deep Condition GZ Curve

Table A29: AOR Variant 2 Deep Condition Hydrostatics					
Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
0.644	11.881	12.203	11.559	-0.134	37,847.27
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
99.086	0.004	10.847	99.08	0.013	6.985
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
92.223	0.007	4,458.253	12.478	315.665	0.238
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0.526	1.631	304.818	1.393	304.292	581.649

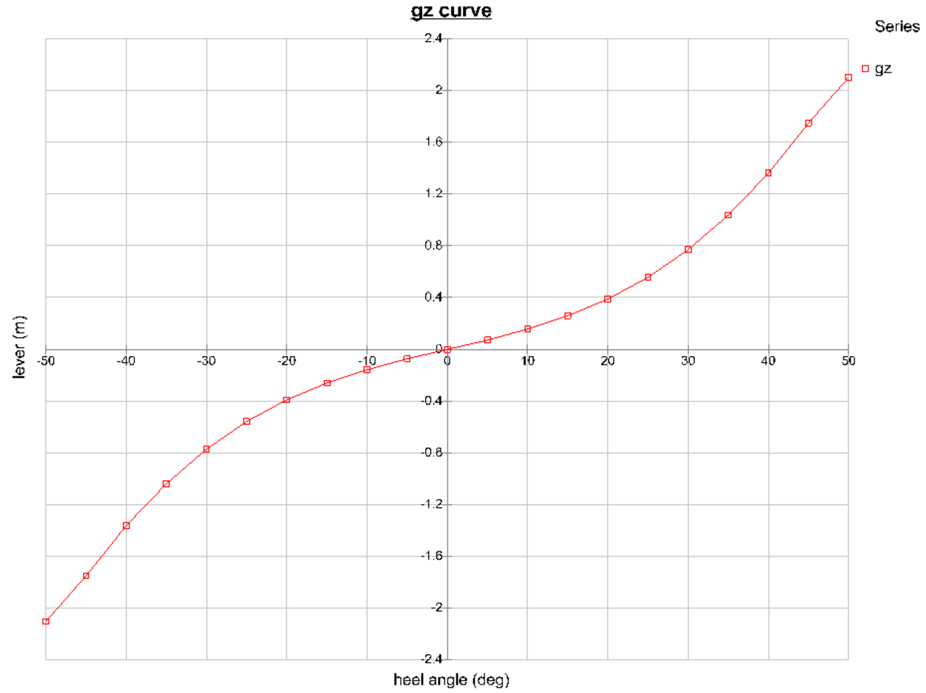


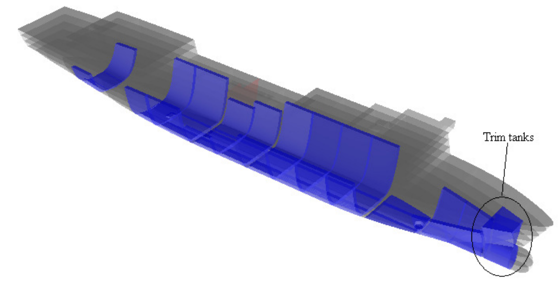
Figure A103: AOR Variant 2 Light Condition GZ Curve

Table A30: AOR Variant 2 Light Condition Hydrostatics

Trim BP (m)	**Mean draught (m)**	**Draught AP (m)**	**Draught FP (m)**	**List or loll angle (deg)**	**Displacement (te)**
1.687	8.413	9.256	7.569	0.101	23,358.25
LCGs (m)	**TCGs (m)**	**VCGs (m)**	**LCB (m)**	**TCB (m)**	**VCB (m)**
101.214	-0.002	10.958	101.171	-0.012	4.991
LCF (m)	**TCF (m)**	**TPI (te/m)**	**KMt (m)**	**KMl (m)**	**FSCt (m)**
92.22	-0.007	3,976.61	11.842	412.799	0.144
FSCl (m)	**GMts (m)**	**GMls (m)**	**GMtf (m)**	**GMlf (m)**	**MCT BP (te m/cm)**
0.577	0.884	401.841	0.741	401.264	473.377

In the case of AOR Variant 2 (deep condition), due to the centroid of the cargo tanks being well forward of the hull envelope centroid, an effort was made to locate heavy items (such as the cargo crane and the containers) aft of amidships (Figure 5.55). This resulted to a large forward portion of the weatherdeck being clear of equipment. However, an unacceptable trim was still produced, leading to the necessity to fill the aft ballast tanks with 560te of seawater. In addition, similarly to the first variant all liquid tanks were subdivided by two longitudinal bulkheads, to prevent lolling (GA, Appendix 8). In the light condition, the adverse effect (an excessive positive trim) resulted, due to the concentration of compartments aft, leading to (only) amidships and forward ballast tanks (located between the double hulls as clearly visible in the GA, Appendix 8) being full, as were the forward trim tanks. The total mass of trim water was 1,490te, i.e. more than double that of AOR Variant 1, although the light condition trim was still considerably larger in AOR Variant 2. The above exploration proves the advantages of locating the stores and tanks in the (wide) central part of the ship, through separating the main machinery compartment forward and aft by deploying an IFEP system, therefore, minimising ballast requirements and complications (Andrews and Pawling 2007) as mentioned in Appendix 2.3. The arrangements of the ballast and trim tanks of the two AOR variants are depicted in Figure A104.

AOR Variant 1



AOR Variant 2

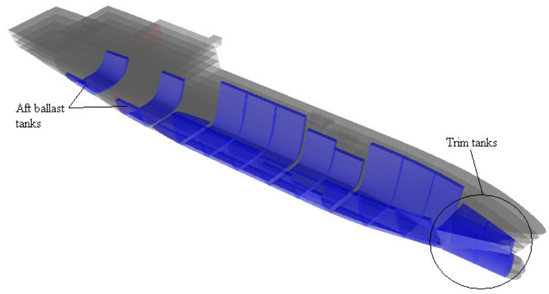


Figure A104: AOR Ballast and Trim Tank Arrangement

Damage stability for both replenishment ship variants was assessed against Defence Standard 02-109 (NES 109) damage criteria assessment (MOD 2000), mentioned in Appendix 4.2. However, contrary to the combatant designs, for the AOR variants damaged stability standards for vessels designed to MOD standards with no military role and vessels designed to legislation with a military role were applied. For vessels between 75m and 200m in waterline length (the two AOR variants having a waterline length of 198.8m and 198.7m respectively) the assumed damage extent is: “Any three adjacent main compartments (excluding large machinery spaces). Where compliance with a three adjacent compartment standard in way of large machinery spaces is clearly demonstrated to the Sea Technology Group as impractical, damage to any two adjacent main compartments in way of main machinery may be accepted” (MOD 2000). Therefore, the cases illustrated in Figure A105 and Figure A106, with the flooded WT sections shown in yellow, were assessed and all criteria were met.

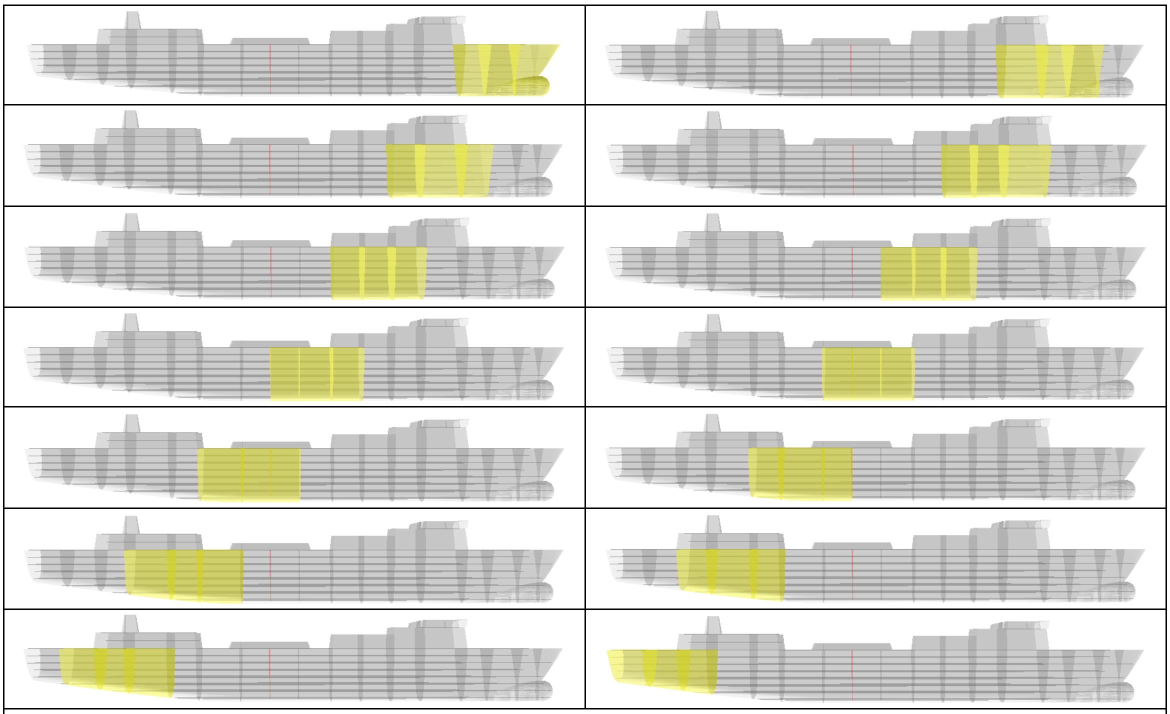


Figure A105: AOR Variant 1 Damage Stability Assessment Cases

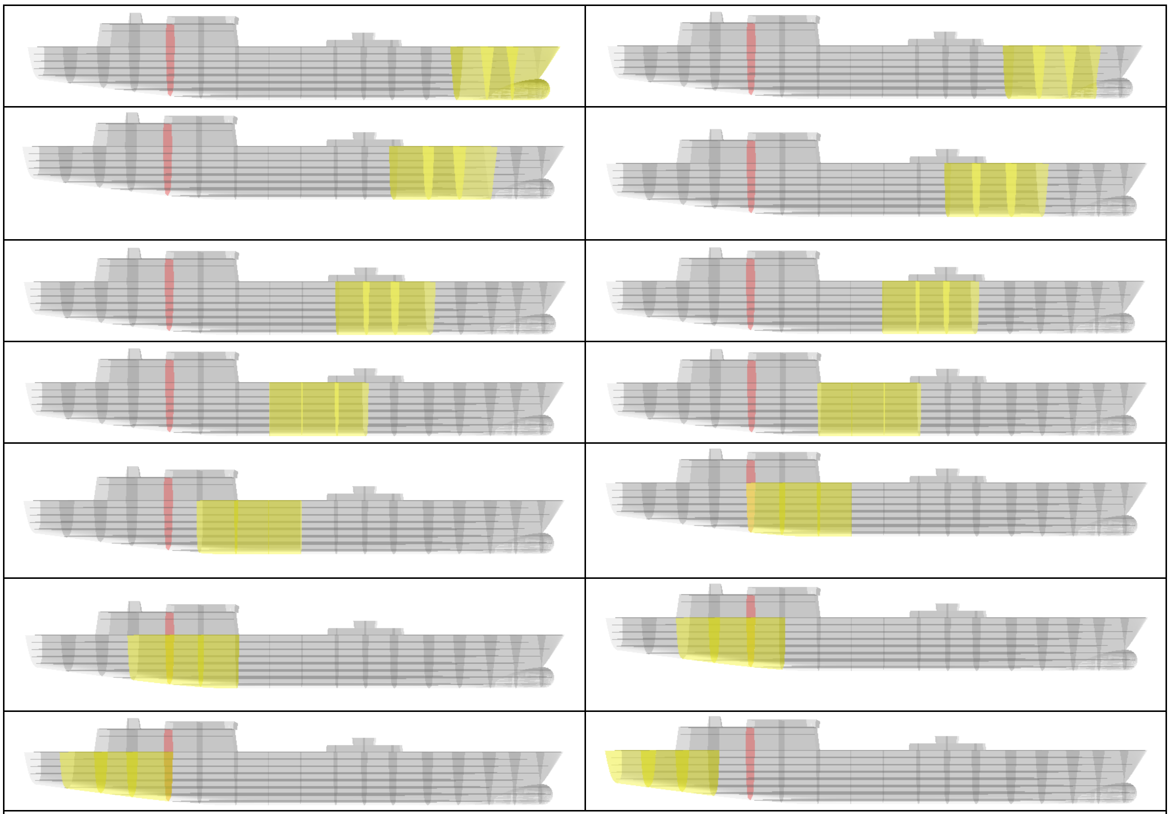


Figure A106: AOR Variant 2 Damage Stability Assessment Cases

A10.1 Frigate Variants (Including Baseline)

<table>
<tr><td colspan="3">Table A31: Weapon System Data for the Three Frigate Variants</td></tr>
<tr><td colspan="2"></td><td rowspan="14">All data is unclassified and was taken from (Fuller 2008; McDonald 2010; UCL 2010b; Army Technology 2011) and thorough discussions with Dstl staff.</td></tr>
<tr><td colspan="2">Attacking ASM</td></tr>
<tr><td>Initial range (m)</td><td>80,000</td></tr>
<tr><td>Radar horizon (m)</td><td>18,300</td></tr>
<tr><td>Missile velocity (m/s)</td><td>315</td></tr>
<tr><td>Launch interval (s)</td><td>2</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">MBDA VL MICA Naval PDMS</td></tr>
<tr><td>Reaction time (s)</td><td>11.5</td></tr>
<tr><td>Launch interval (s)</td><td>2</td></tr>
<tr><td>Maximum range (sea-skimming ASM) (m)</td><td>6,000</td></tr>
<tr><td>Minimum range (m)</td><td>1,300</td></tr>
<tr><td>Velocity (m/s)</td><td>1,190</td></tr>
<tr><td>Kill assessment (s)</td><td>6</td></tr>
</table>

The radar horizon for each ship design was calculated through the following expression:

$$\text{Radar Horizon (in km)} = 3.6 \times \sqrt{h}, \qquad (12)$$

Where, h is equal to the height of the surveillance or MF radar (central to the PDMS for, often multiple, threat detection, evaluation and weapon assignment (Longworth 1983; Adams 1988)) in metres. The radar horizon for each frigate design variant is therefore, slightly different, as shown in Table A32.

Table A32: Radar Horizon for the Three Frigate Variants

Ship	Surv. Radar Centroid (m)	Mean Deep Draught (m)	h (m)	Radar Horizon (km)
Frigate Variant 1	31.0	4.0	27.0	18.7
Frigate Variant 2	30.7	4.4	26.3	18.5
Frigate Variant 3	31.0	5.2	25.9	18.3

However, since the maximum defensive missile range is much smaller than the radar horizon of all frigate variants, these differences did not affect the susceptibility calculations. Therefore, the minimum radar horizon (i.e. that of the third variant) was assumed for all frigates. Note that although the trimaran variant had the smallest radar horizon, this could relatively easily (compared to a monohull design) be increased by moving the side hulls further outboard.

The data in Table A33 was used in order to obtain the following sequence of events for the case of each of the frigate design variant being under attack by four sea-skimming ASM.

Table A33: Sequence of Events for the Three Frigate Variants			
Event	**Time (s)**	**Range (m)**	**Remarks**
Start (ASM 1 launch)	0	80,000	Not detected
ASM 1 detected	196	18,300	Crosses radar horizon
ASM 2 detected	198		2s interval
ASM 3 detected	200		2s interval
ASM 4 detected	202		2s interval
VLS ready	207	14,677	11.5s reaction time
VLS fire 1	230	7,588	To engage at 6,000m
VLS fire 2	232	6,958	2s interval
Hit 1	235	6,000	
Hit 2	237	5,502	
Kill assessment	243	3,612	6s kill assessment
VLS fire 3	243	3,612	
VLS fire 4	245	2,982	2s interval
Hit 3	245	2,856	
Hit 4	246	2,358	
Kill assessment	252	468	6s kill assessment
VLS fire 5	252	468	Not fired - below minimum range

A10.2 Corvette, Baseline Frigate and Destroyer

The Corvette design had identical AAW systems to the frigate designs (Table 5.4); therefore resulting to an identical combat system reaction timeline (illustrated in Table A33 and Figure 6.2 from data given in Table A31). The radar horizon of the Corvette was larger than the minimum range against sea-skimming threats of the defensive missile, therefore, not affecting the results. Radar horizon data for the three combatants were obtained using Equation 12, and are presented in Table A34.

Table A34: Radar Horizon for the Corvette, Baseline Frigate and Destroyer				
Ship	**SR/MFR Centroid (m)**	**Mean Deep Draught (m)**	**h (m)**	**Radar Horizon (km)**
Corvette	24.3	3.9	20.4	16.3
Frigate Variant 1	31.0	4.0	27.0	18.7
Destroyer	35.0	4.7	30.3	19.8

Since the Destroyer design had a different, AAW capability (Table 5.4), the CSEE method had to be reapplied in this case. Weapon system data are shown in Table A35, noting that it was initially assumed that only Aster-15 (rather than Aster-30) SAMs would be deployed, and the threat characteristics are consistent with the previous cases.

Table A35: Weapon System Data for the Destroyer

		All data is unclassified and was taken from (Friedman 2006; Fuller 2008; McDonald 2010; UCL 2010b; Beedall 2011a; MBDA 2012) and thorough discussions with Dstl staff.
Attacking ASM		
Initial range (m)	80,000	
Radar horizon (m)	19,800	
Missile velocity (m/s)	315	
Launch interval (s)	2	
PAAMS ADMS (Aster-15 SAMs)		
Reaction time (s)	4	
Launch interval (s)	0.21	
Maximum range (sea-skimming ASM) (m)	15,000	
Minimum range (m)	1,700	
Velocity (m/s)	1,020	
Kill assessment (s)	3	
Phalanx CIWS		
Detection range (m)	10,000	
Reaction time (s)	7	
Maximum range (m)	1,000	
Minimum range (m)	100	
Velocity (m/s)	1,000	
Maximum burst (s)	3.25	
Kill assessment (s)	5	

The Phalanx CIWS detection range is different to the Destroyer's radar horizon since the CIWS is an independent system with its own radar; in addition, the SAM launch interval was estimated by assuming that eight missiles can be fired in 10s and there are six launchers in the Destroyer (Beedall 2011a). The data above was used to produce the sequence of events shown in Table A36 for the scenario of the Destroyer being attacked by four ASMs. (Note that, by the time the PAAMS ADMS is ready to fire the first Aster-15 missile, this missile will reach the attacking ASM within the maximum range, therefore, implying that the MFR should be positioned higher in order to increase the radar horizon. This was not observed in the case of the frigates and Corvettes MBDA VL MICA Naval PDMS (Table A33)).

Table A36: Sequence of Events for the Destroyer			
Event	**Time (s)**	**Range (m)**	**Remarks**
Start (ASM 1 launch)	0	80,000	Not detected
ASM 1 detected	191	19,800	Crosses radar horizon
ASM 2 detected	193		2s interval
ASM 3 detected	195		2s interval
ASM 4 detected	197		2s interval
VLS ready	195	18,540	4s reaction time
VLS fire 1	195	18,540	
VLS fire 2	195	18,474	0.21 interval
Hit 1	209	14,165	Already within maximum range
Hit 2	209	14,115	
Kill assessment	212	13,170	3s kill assessment
VLS fire 3	212	13,170	
VLS fire 4	212	13,105	0.21 interval
Hit 3	222	10,063	
Hit 4	222	10,013	
Kill assessment	225	9,068	3s kill assessment
VLS fire 5	225	9,068	
VLS fire 6	225	9,002	0.21 interval
Hit 5	232	6,928	
Hit 6	232	6,878	
Kill assessment	235	5,933	3s kill assessment
VLS fire 7	235	5,933	
VLS fire 8	235	5,867	0.21 interval
Hit 7	240	4,533	
Hit 8	240	4,483	
Kill assessment	243	3,538	3s kill assessment
VLS fire 9	243	3,538	
VLS fire 10	243	3,472	0.21 interval
Hit 9	245	2,703	
Hit 10	246	2,653	
Kill assessment	249	1,708	3s kill assessment
VLS fire 11	249	1,708	
VLS fire 12	249	1,642	Not fired - below minimum range
Hit 11	250	1,305	
Kill assessment	253	310	3s kill assessment
Phalanx detect	222	10000	
Phalanx ready	229	7795	7s reaction time
Fire 1	250	1315	To engage at 1,000m
Hit 1	251	1000	
Fire 1 stop	253	291	3.25s burst
Hit 1 stop	253	221	
Kill assessment	258	-1284	Ship hit

A10.3 AOR Variants

<table>
<tr><td colspan="3">Table A37: Weapon System Data for the Two AOR Variants</td></tr>
<tr><td colspan="2"></td><td rowspan="15">All data is unclassified and was taken from (Friedman 2006; Fuller 2008; McDonald 2010; UCL 2010b) and thorough discussions with Dstl staff.</td></tr>
<tr><td colspan="2">Attacking ASM</td></tr>
<tr><td>Initial range (m)</td><td>80,000</td></tr>
<tr><td>Radar horizon (m)</td><td>20,500</td></tr>
<tr><td>Missile velocity (m/s)</td><td>315</td></tr>
<tr><td>Launch interval (s)</td><td>2</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Raytheon SeaRAM Weapon System</td></tr>
<tr><td>Reaction time (s)</td><td>6</td></tr>
<tr><td>Launch interval (s)</td><td>5</td></tr>
<tr><td>Maximum range (sea-skimming ASM) (m)</td><td>4,630</td></tr>
<tr><td>Minimum range (m)</td><td>1,100</td></tr>
<tr><td>Velocity (m/s)</td><td>650</td></tr>
<tr><td>Kill assessment (s)</td><td>6</td></tr>
</table>

The radar horizon (calculated by Equation 12) was much larger than the defensive missiles maximum range against sea-skinning missiles, therefore, not affecting the CSEE results. Radar horizon data for the two auxiliary ship designs are given in Table A38; the smaller of these values was used in the CSEE.

Table A38: Radar Horizon for the Two AOR Variants

Ship	**Surv. Radar Centroid (m)**	**Mean Deep Draught (m)**	**h (m)**	**Radar Horizon (km)**
AOR Variant 1	44.5	12.0	32.5	20.5
AOR Variant 2	45.1	11.9	33.2	20.7

The above data was then used in order to obtain the sequence of events from the launch of the first ASM against the AOR designs, until the last (fourth) one hits the ship, shown Table A39.

Table A39: Sequence of Events for the Two AOR Variants

Event	**Time (s)**	**Range (m)**	**Remarks**
Start (ASM 1 launch)	0	80,000	Not detected
ASM 1 detected	189	20,500	Crosses radar horizon
ASM 2 detected	191		2s interval
ASM 3 detected	193		2s interval
ASM 4 detected	195		2s interval
SeaRAM ready	195	18,610	6s reaction time
SeaRAM fire 1	232	6,874	To engage at 4,630m
SeaRAM fire 2	237	5,299	5s interval
Hit 1	239	4,630	
Hit 2	243	3,569	
Kill assessment	249	1,679	6s kill assessment
SeaRAM fire 3	249	1,679	
SeaRAM fire 4	254	104	Not fired - below minimum range
Hit 3	250	1,131	
Kill assessment	260	-1,820	Ship hit

A10.4 Destroyer Sensitivity Studies

Table A40: Sequence of Events for the Destroyer (Aster-30, MFR horizon limited)

Event	Time (s)	Range (m)	Remarks
Start (ASM 1 launch)	0	80,000	Not detected
ASM 1 detected	191	19,800	Crosses radar horizon
ASM 2 detected	193		2s interval
ASM 3 detected	195		2s interval
ASM 4 detected	197		2s interval
VLS ready	195	18,540	4s reaction time
VLS fire 1	195	18,540	
VLS fire 2	195	18,474	0.21 interval
Hit 1	205	15,375	Already within maximum range
Hit 2	205	15,320	
Kill assessment	208	14,375	3s kill assessment
VLS fire 3	208	14,375	
VLS fire 4	209	14,310	0.21 interval
Hit 3	216	11,921	
Hit 4	216	11,866	
Kill assessment	219	10,921	3s kill assessment
VLS fire 5	219	10,921	
VLS fire 6	220	10,856	0.21 interval
Hit 5	225	9,057	
Hit 6	225	9,002	
Kill assessment	228	8,057	3s kill assessment
VLS fire 7	228	8,057	
VLS fire 8	229	7,992	0.21 interval
Hit 7	233	6,682	
Hit 8	233	6,627	
Kill assessment	236	5,682	3s kill assessment
VLS fire 9	236	5,682	
VLS fire 10	236	5,617	0.21 interval
Hit 9	239	4,712	
Hit 10	239	4,658	
Kill assessment	242	3,713	3s kill assessment
VLS fire 11	242	3,713	
VLS fire 12	242	3,647	0.21 interval
Hit 11	244	3,079	
Hit 12	244	3,024	
Kill assessment	247	2,079	3s kill assessment
VLS fire 13	247	2,079	Not fired - below minimum range
Phalanx detect	222	10,000	
Phalanx ready	229	7,795	7s reaction time
Fire 1	250	1,315	To engage at 1,000m
Hit 1	251	1,000	

Fire 1 stop	253	291	3.25s burst
Hit 1 stop	253	221	
Kill assessment	258	-1,284	Ship hit

Table A41: Sequence of Events for the Destroyer (Aster-30, Maximum Range limited)

Event	**Time (s)**	**Range (m)**	**Remarks**
Start (ASM 1 launch)	0	80,000	Not detected
ASM 1 detected	191	19,800	Crosses radar horizon
ASM 2 detected	193		2s interval
ASM 3 detected	195		2s interval
ASM 4 detected	197		2s interval
VLS ready	195	18,540	4s reaction time
VLS fire 1	139	36,176	To engage at 30,000m
VLS fire 2	139	36,111	0.21 interval
Hit 1	159	30,000	
Hit 2	159	29,946	
Kill assessment	162	29,001	3s kill assessment
VLS fire 3	162	29,001	
VLS fire 4	162	28,935	0.21 interval
Hit 3	178	24,049	
Hit 4	178	23,995	
Kill assessment	181	23,050	3s kill assessment
VLS fire 5	181	23,050	
VLS fire 6	181	22,984	0.21 interval
Hit 5	193	19,115	
Hit 6	193	19,060	
Kill assessment	196	18,115	3s kill assessment
VLS fire 7	196	18,115	
VLS fire 8	197	18,049	0.21 interval
Hit 7	206	15,022	
Hit 8	206	14,968	
Kill assessment	209	14,023	3s kill assessment
VLS fire 9	209	14,023	
VLS fire 10	210	13,957	0.21 interval
Hit 9	217	11,629	
Hit 10	217	11,574	
Kill assessment	220	10,629	3s kill assessment
VLS fire 11	220	10,629	
VLS fire 12	220	10,564	0.21 interval
Hit 11	226	8,815	
Hit 12	226	8,760	
Kill assessment	229	7,815	3s kill assessment
VLS fire 13	229	7,815	
VLS fire 14	229	7,749	0.21 interval
Hit 13	233	6,481	

Hit 14	234	6,426	
Kill assessment	237	5,481	3s kill assessment
VLS fire 15	237	5,481	
VLS fire 16	237	5,416	0.21 interval
Hit 15	240	4,546	
Hit 16	240	4,491	
Kill assessment	243	3,546	3s kill assessment
VLS fire 17	243	3,546	
VLS fire 18	243	3,481	0.21 interval
Hit 17	245	2,941	
Hit 18	245	2,886	
Kill assessment	248	1,941	3s kill assessment
VLS fire 19	248	1,941	Not fired - below minimum range
Phalanx detect	222	10,000	
Phalanx ready	229	7,795	7s reaction time
Fire 1	250	1,315	To engage at 1,000m
Hit 1	251	1,000	
Fire 1 stop	253	291	3.25s burst
Hit 1 stop	253	221	
Kill assessment	258	-1,284	Ship hit

As expected, in Table A41 the first Aster-30 missile is fired before the PAAMS ADMS is ready. In order for this not to occur, and the AAW system to be able to utilise its full capability, the MFR horizon would have to be increased to approximately 37 440m, meaning that (according to Equation 12) the MFR would have to be located approximately 108m above the waterline. This is clearly unrealistic for a combatant design, although it has to be noted that the above is relevant only to sea-skimming ASMs.

The vulnerability percentages shown in the tables in this appendix are averaged given a hit in each WT section (or in the entire dimension of the design in the case of Appendix 11.4) from the port or starboard side.

A11.1 Frigate Variants (Including Baseline)

Table A42: Vulnerability Results Given a Hit at Each WT Section of Frigate Variant 1

WT Section		M	L	K	J	I	H	G	F	E	D	C	B	A
MOVE	Move system	0	45.5	45.2	26.1	0	0	0	0	0	0	0	0	0
FIGHT	Naval gun system	0	0	0	0	0	0	23.8	41.5	0	82	100	25	0
	ASM system	0	0	0.4	0.5	0	75	42.1	25.6	50	0	0	0	0
	Aft SAM system	0	0	1.5	69.5	33.3	0	0	0	0	0	0	0	0
	Fwd SAM system	0	0	0	0	0	0	0	0	75	100	88.9	0	0
	Helicopter system	100	100	69.8	65.6	1.8	0	18.8	26.4	50	36.4	44.4	0	0

Table A43: Vulnerability Results Given a Hit at Each WT Section of Frigate Variant 2

WT Section		M	L	K	J	I	H	G	F	E	D	C	B	A
MOVE	Move system	0	33.3	66.7	25	0	0	0	0	0	0	0	0	0
FIGHT	Naval gun system	0	0	0	0	0	0	22.7	32.6	0	100	100	18.2	0
	ASM system	95.9	100	51.7	0	0	0	15.7	25	33.3	0	0	0	0
	Aft SAM system	0	3.3	97.7	33.4	0	0	0.05	0	0	0	0	0	0
	Fwd SAM system	0	0	0	0	0	0	0.05	0	83.4	100	76.9	0	0
	Helicopter system	0	0	33.3	75	100	100	47.4	31.6	33.3	30.8	30.8	0	0

Table A44: Vulnerability Results Given a Hit at Each WT Section of Frigate Variant 3															
WT Section		**N**	**M**	**L**	**K**	**J**	**I**	**H**	**G**	**F**	**E**	**D**	**C**	**B**	**A**
MOVE	Move system	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FIGHT	Naval gun system	0	0	0	0	0	0	0	57.1	7.7	0	100	100	50	0
	ASM system	0	0	0	0	0	1.6	19.4	0	30.8	50	0	0	0	0
	Aft SAM system	100	100	21.4	0	0	0	0	0	0	0	0	0	0	0
	Fwd SAM system	0	0	0	0	0	0	0	0	30.8	100	42.9	0	0	0
	Helicopter system	0	0	78.6	75	65.4	66.7	6.1	4.95	30.8	50	42.9	0	0	0

A11.2 Corvette and Destroyer

Table A45: Vulnerability Results Given a Hit at Each WT Section of the Corvette										
WT Section		**I**	**H**	**G**	**F**	**E**	**D**	**C**	**B**	**A**
MOVE	Move system	0	0	0	0	0	0	0	0	0
FIGHT	Naval gun system	0	0	0	0	17.1	81.8	100	86.4	25
	ASM system	0	0	0	41	72.2	35.7	37.5	0	0
	Aft SAM system	38.3	33.3	69.2	0	3.7	0	0	0	0
	Fwd SAM system	0	0	0	0	0	38.1	100	72.7	0
	Helicopter system	100	100	100	0	22.7	37.1	59.4	81.8	0

Table A46: Vulnerability Results Given a Hit at Each WT Section of the Destroyer															
WT Section		**N**	**M**	**L**	**K**	**J**	**I**	**H**	**G**	**F**	**E**	**D**	**C**	**B**	**A**
MOVE	Move system	0	27.3	38.1	12.8	0	0	0	0	0	0	0	0	0	0
FIGHT	Naval gun system	0	0	0	0	0	0	0	0	5	20.8	100	100	18.8	0
	ASM system	0	0	0	0	0	0	4.5	92.4	50.3	66.7	0	0	0	0
	Aft SAM system	0	0	0	2.3	75	1.6	1.7	0.7	1.6	0	0	0	0	0
	Fwd SAM system	0	0	0	1.6	0.8	1.6	1.7	0.7	13.8	100	0	0	0	0
	Helicopter system	61.8	100	100	20.5	0	0	1.2	38.4	37	66.7	0	58.3	31.3	0

A11.3 AOR Variants

Table A47: Vulnerability Results Given a Hit at Each WT Section of AOR Variant 1

WT Section		Q	P	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
MOVE	Move system	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FIGHT	Ability to RAS AVCAT	0	0	0	0	0	0	0	0	0	0	0	0	25.7	0	0	0	0
	Ability to RAS dieso	0	0	0	0	0	0	0	0	0	0	0	0	25.7	0	0	0	0
	Ability to RAS dry stores	0	0	0	0	0	0	62.1	62.1	0	0	0	0	25.7	0	0	0	0
	Ability to RAS ordnance	0	0	0	0	0	0	62.1	62.1	0	0	0	0	25.7	0	0	0	0
	Aviation support	37.5	66.7	81.6	58.5	64.3	19.4	20.7	20.7	24	0	0	0	0	0	0	0	0
	CIWS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A48: Vulnerability Results Given a Hit at Each WT Section of AOR Variant 2

WT Section		Q	P	O	N	M	L	K	J	I	H	G	F	E	D	C	B	A
MOVE	Move system	31.6	33.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FIGHT	Ability to RAS AVCAT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ability to RAS dieso	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Ability to RAS dry stores	0	0	0	0	0	0	0	0	0	58.1	58.1	0	0	0	0	0	0
	Ability to RAS ordnance	0	0	0	0	0	0	0	0	0	58.1	58.1	0	0	0	0	0	0
	Aviation support	36.8	66.7	63.1	60.8	57.3	22.7	0	0	0	0	0	0	0	0	0	0	0
	CIWS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

A11.4 ASM Attack Angle Variation

Table A49: Effect of ASM Attack Angle on System Vulnerability for the Destroyer

	ASM attack azimuth (deg)	ASM attack elevation (deg)	Vulnerability (%)					
			Move system	Naval gun system	ASM system	Aft SAM system	Fwd SAM system	Helicopter system
Stern	0/360	0	0	0	0	0	0	47.9
	45	0	14.6	11.7	17	4.8	0.4	36.1
Port	90	0	14.3	7.7	19.7	6.2	5.5	47.7
	135	0	12	10	25.8	2	4	42
Bow	180	0	0	17.2	13.8	0	0.1	6.9
Port	90	45	5	10.6	10.7	7.7	5.2	37.7

Appendix 12: Weighting Scheme Form

Name (optional):...
Rank:..
Specialisation:...

SCENARIO 1	
Threats present	Air and submarine
Location	Blue water

SCENARIO 2	
Threats present	Air, shore based missiles and gun batteries
Location	Littoral

SCENARIO 3	
Threats present	Air and surface (missile firing)
Location	Littoral

		SCENARIO 1	SCENARIO 2	SCENARIO 3
Category 1 (FLOAT)	Float			
Category 2 (Recovery support)	Recovery.support			
Category 3 (MOVE and FIGHT)	Move			
	Gun			
	ASM			
	Aft SAM			
	Fwd SAM			
	ASW/Helicopter			

Immediate DCFF Performance Factors (Category 1)

PF	Weighting
Average distance between FRPP and damaged compartment centre	
Average number of WTD operated per FRP	
Number of internal decks in damaged compartment	
Average total width of alternative routes	
ATU, ventilation and smoke clearance (of damaged zone)	
Fire pump (of damaged zone)	
Overall fire pump system	
NBCD stores - aft FRPP	
NBCD stores - fwd FRPP	
Remaining NBCD stores (2)	
Power (of damaged zone)	
Overall power system	
SCC (HQ1)	
Bridge (HQ2)	
Ops. Room	
Aft FRPP	
Fwd FRPP	

Major System Recovery Performance Factors (Category 2)

PF	Weighting
Aft workshops	
Fwd workshops	
Naval stores	
Aft spare gear stores	
Fwd spare gear stores	
SCC (updated value including fire effects)	
Ops. Room (updated value including fire effects)	

Individual Major System Recovery Performance Factors (Category 3)

PF	Weighting
How important is it for the system to be functioning because of redundancy	
How important is it for the system to be functioning 100%	
How important is access to the hit WT section	
How important is access from the damaged equipment to the naval stores	
How important is access from the damaged equipment to the aft spare gear store	
How important is access from the damaged equipment to the aft workshops	
How important is access from the damaged equipment to the fwd spare gear stores	
How important is access from the damaged equipment to the fwd workshops	

A13.1 UPC Analysis Data and Results

Weight Group UPC Data

Table A50: Frigate Variant 1 Weight Group UPC Data

UCL Ship Design Exercise Weight and Space Classification System		Weight (te)	Material/Equipment (£k - 2008)	Labour/Installation (hr)	Labour/Installation (£k - 2008)
		3055			
10	General	87			
11	Fittings	48			
12	Navigation	49			
13	Anchoring, mooring, RAS	34			
14	Offices	5			
15	Workshops	12			
16	Structure	1579	2996	750037	37622
17	Stores	62			
Group 1		1875			
Group 1 - 16		296	2727	303849	15241
20	Accommodation	69			
21	Personnel support	9			
22	Stores	28			
23	Miscellaneous	27			
Group 2		134	1229	136890	6866
31	Air conditioning, ventilation and CW system	105	1832	119218	5980
32	Sea and fresh water system	123	2075	135203	6782
33	Fuel systems	37	490	31909	1601
34	Auxilliary Steam	0			
35	Hydraulic systems	0			
36	Compressed air systems	23	337	21963	1102
37	Waste disposal system	13	227	14738	739
38	Stabilisers	0			
39	Aircraft systems	11	98	6300	316
Group 3		312			
41	Gas turbines	81	Specific item cost	25468	1277
42	Diesel Engines	170	Specific item cost	53449	2681
43	Steam Turbines	0			
44	Electric motor	84	Specific item cost	26460	1327
45	Engine auxiliary machinery	0			
46	Gearbox	0			
47	Transmission	53	1296	6336	318
48	Propulsor	20	502	2453	123
49	Ducting	47	1071	5351	268
Group 4		454			
51	Electrical power generation	0			
52	Electrical power distribution equipment	37	1016	66235	3322
53	General distribution	105	4355	283482	14219
54	Lighting systems	0			
Group 5		142			
61	Weapons control systems	7	Specific item cost	124207	6230
62	External communication	23	Specific item cost	27721	1390
63	Sonars	10	Specific item cost	27257	1367
64	Radars	6	Specific item cost	130630	6552
65	EW systems	3	Specific item cost	63852	3203
66	Weapon and missile systems	88	Specific item cost	856466	42960
67	Minehunting	0			
68	Aircraft	0			
Group 6		137			
71	Naval stores and spare gear	0			
72	Victualling and medical stores	0			
73	Weapon stores	0			
74	Stowed liquids	0			
75	Operating liquids	0			
76	Ammunitions	0			
77	Aircraft	0			
78	Vehicles	0			
79	Cargo	0			
Group 7		0			
81	Growth margin	0			
82	Board margin	0			
Group 8		0			
Total		3055			

Table A51: Frigate Variant 2 Weight Group UPC Data

UCL Ship Design Exercise Weight and Space Classification System		Weight (te)	Material/Equipment (£k - 2008)	Labour/Installation (hr)	Labour/Installation (£k - 2008)
		3224			
10	General	105			
11	Fittings	48			
12	Navigation	51			
13	Anchoring, mooring, RAS	36			
14	Offices	5			
15	Workshops	12			
16	Structure	1660	3150	788456	39549
17	Stores	65			
Group 1		1983			
Group 1 - 16		323	2971	330992	16603
20	Accommodation	70			
21	Personnel support	9			
22	Stores	29			
23	Miscellaneous	28			
Group 2		136	1255	139802	7012
31	Air conditioning, ventilation and CW system	105	1837	119510	5995
32	Sea and fresh water system	125	2096	136577	6851
33	Fuel systems	35	466	30348	1522
34	Auxilliary Steam	0			
35	Hydraulic systems	0			
36	Compressed air systems	23	338	22085	1108
37	Waste disposal system	13	228	14794	742
38	Stabilisers	0			
39	Aircraft systems	11	98	6300	316
Group 3		312			
41	Gas turbines	81	Specific item cost	25468	1277
42	Diesel Engines	219	Specific item cost	68994	3461
43	Steam Turbines	0			
44	Electric motor	84	Specific item cost	26460	1327
45	Engine auxiliary machinery	0			
46	Gearbox	0			
47	Transmission	53	1296	6336	318
48	Propulsor	20	502	2453	123
49	Ducting	54	1249	6244	313
Group 4		511			
51	Electrical power generation	0			
52	Electrical power distribution equipment	37	1024	66812	3351
53	General distribution	106	4408	286945	14393
54	Lighting systems	0			
Group 5		144			
61	Weapons control systems	7	Specific item cost	124207	6230
62	External communication	23	Specific item cost	27721	1390
63	Sonars	10	Specific item cost	27257	1367
64	Radars	6	Specific item cost	130630	6552
65	EW systems	3	Specific item cost	63852	3203
66	Weapon and missile systems	89	Specific item cost	859203	43098
67	Minehunting	0			
68	Aircraft	0			
Group 6		138			
71	Naval stores and spare gear	0			
72	Vicutalling and medical stores	0			
73	Weapon stores	0			
74	Stowed liquids	0			
75	Operating liquids	0			
76	Ammunitions	0			
77	Aircraft	0			
78	Vehicles	0			
79	Cargo	0			
Group 7		0			
81	Growth margin	0			
82	Board margin	0			
Group 8		0			
Total		3224			

Table A52: Frigate Variant 3 Weight Group UPC Data

UCL Ship Design Exercise Weight and Space Classification System		Weight (te)	Material/Equipment (£k - 2008)	Labour/Installation (hr)	Labour/Installation (£k - 2008)
		3567			
10	General	110			
11	Fittings	51			
12	Navigation	36			
13	Anchoring, mooring, RAS	36			
14	Offices	6			
15	Workshops	14			
16	Structure	1859	3527	882852	44284
17	Stores	72			
Group 1		2184			
Group 1 - 16		325	2989	333035	16705
20	Accommodation	75			
21	Personnel support	10			
22	Stores	31			
23	Miscellaneous	30			
Group 2		145	1338	149084	7478
31	Air conditioning, ventilation and CW system	108	1890	122936	6166
32	Sea and fresh water system	139	2342	152658	7657
33	Fuel systems	44	578	37679	1890
34	Auxilliary Steam	0			
35	Hydraulic systems	0			
36	Compressed air systems	25	360	23519	1180
37	Waste disposal system	13	230	14964	751
38	Stabilisers	0			
39	Aircraft systems	11	98	6300	316
Group 3		340			
41	Gas turbines	81	SIC	25468	1277
42	Diesel Engines	170	SIC	53449	2681
43	Steam Turbines	0			
44	Electric motor	86	SIC	27188	1364
45	Engine auxiliary machinery	0			
46	Gearbox	0			
47	Transmission	33	800	3909	196
48	Propulsor	60	1482	7241	363
49	Ducting	47	1089	5444	273
Group 4		477			
51	Electrical power generation	0			
52	Electrical power distribution equipment	41	1129	73607	3692
53	General distribution	122	5033	327631	16434
54	Lighting systems	0			
Group 5		162			
61	Weapons control systems	7	SIC	124207	6230
62	External communication	23	SIC	27721	1390
63	Sonars	10	SIC	27257	1367
64	Radars	6	SIC	130630	6552
65	EW systems	3	SIC	63852	3203
66	Weapon and missile systems	87	SIC	844005	42335
67	Minehunting	0			
68	Aircraft	0			
Group 6		136			
71	Naval stores and spare gear	0			
72	Vicutalling and medical stores	0			
73	Weapon stores	0			
74	Stowed liquids	122			
75	Operating liquids	0			
76	Ammunitions	0			
77	Aircraft	0			
78	Vehicles	0			
79	Cargo	0			
Group 7		122			
81	Growth margin	0			
82	Board margin	0			
Group 8		0			
Total		3567			

Specific Item Cost Data

Table A53: Frigate Variant 1, Group 4 Specific Item Cost Data

Classification	Type	Quantity	Cost per item (£k - 2008)	Total cost (£k - 2008)	Source
41	Rolls-Royce MT30	1	7223	7223	(UCL 2010b)
42	Wartsila 9L26	2	1934	3869	(UCL 2010b)
42	Wartsila 16V200	2	1934	3869	(UCL 2010b)
44	HTS motor (20MW)	2	8418	16836	(Beedall 2011b)

Table A54: Frigate Variant 2, Group 4 Specific Item Cost Data

Classification	Type	Quantity	Cost per item (£k - 2008)	Total cost (£k - 2008)	Source
41	Rolls-Royce MT30	1	7223	7223	(UCL 2010b)
42	Wartsila 16V26	2	2239	4478	(UCL 2010b)
42	Wartsila 16V200	2	1934	3869	(UCL 2010b)
44	HTS motor (20MW)	2	8418	16836	(Beedall 2011b)

Table A55: Frigate Variant 3, Group 4 Specific Item Cost Data

Classification	Type	Quantity	Cost per item (£k - 2008)	Total cost (£k - 2008)	Source
41	Rolls-Royce MT30	1	7223	7223	(UCL 2010b)
42	Wartsila 9L26	2	1934	3869	(UCL 2010b)
42	Wartsila 16V200	2	1934	3869	(UCL 2010b)
44	HTS motor (37MW)	1	15574	15574	(Beedall 2011b)
44	HTS motor (3.5MW)	1	1473	1473	(Beedall 2011b)

Table A56: Frigate Variant 1, 2 and 3, Group 6 Specific Item Cost Data

Classification	Type	Quantity	Cost per item (£k - 2008)	Total cost (£k - 2008)	Source
61	Operations Room (BAE Systems SSCS with links 11 ,14&16)	1	3687	3687	(UCL 2010b)
62	Generic satellite communications system	2	970	1940	(UCL 2010b)
62	Communications equipment spaces	1	3687	3687	(UCL 2010b)
63	Spherion hull mounted sonar	1	2000	2000	(UCL 2010b)
63	SSTDS (winch, processing cabinet + 2 x launchers ans LCUs)	1	1000	1000	(UCL 2010b)
64	Single face SR STAR Surveillance Radar	1	3500	3500	(UCL 2010b)
64	Navigation Radar	2	1000	2000	(UCL 2010b)
64	General Purpose Electro Optical Device	1	2000	2000	(UCL 2010b)
64	Thales Sirius IRST	2	2000	4000	(UCL 2010b)
65	Raytheon AN SLQ 32 V3 Shipboard ESM ECM System	1	4540	4540	(UCL 2010b)
66	BAE Systems 155mm gun	1	7340	7340	(UCL 2010b)
66	MSI Seahawk 30mm	2	577	1154	(UCL 2010b)
66	Harpoon launchers	2	4750	9500	(UCL 2010b)
66	MBDA VL MICA Naval	4	2250	9000	(UCL 2010b)
66	Rheinmetall MASS Decoy Launchers	4	500	2000	(UCL 2010b)
66	Triple barrel torpedo tubes	2	250	500	(UCL 2010b)

Cost Margins

Table A57: UPC Analysis Cost Margins			
	Frigate Variant 1	**Frigate Variant 2**	**Frigate Variant 3**
Design contingency margin (%)	5	6	7
Minor equipment margin (%)			8
Industrial contingency margin - lack of positive data (%)			10
Displacement correction factor	1.005	0.997	0.985

The design contingency margin (Dirksen 1996; UCL 2010a) was applied to all costs apart from the payload equipment costs. The increase of this margin through the ship variants is an attempt to account for the increase in unconventionality between them. The minor equipment and industrial contingency margins (Dirksen 1996) were applied to all payload items, while the displacement correction factors, taken from a relationship found in (Dirksen 1996), were applied since the parametric relationships used relate to a 4,000te ship. The above procedure is summarised in Table A58, Table A59 and Table A60.

UPC Analysis Results

Table A58: Frigate Variant 1 UPC				
Group		**Cost (£k)**	**Margins (£k)**	**Total Cost (£k)**
1	**Hull**	58,586		
2	**Personnel**	8,095		
3	**Ship systems**	21,577		
4	**Main propulsion**	40,660		
5	**Electric power**	22,912		
6	**Payload (labour/installation)**	61,703		
7	**Variable**	0		
8	**Margins**	0		
	Sub Total	213,534		
	Design contingency margin		10,676	
	Sub Total			224,210
6	**Payload (equipment)**	57,848		
	Minor equipment margin		4,627	
	Industrial contingency margin - lack of positive data		5,784	
	Sub Total			68,261
	Sub Total			292,472
	Displacement correction		1,462	
			TOTAL UPC	**293,934**

Table A59: Frigate Variant 2 UPC				
Group		**Cost (£k)**	**Margins (£k)**	**Total Cost (£k)**
1	**Hull**	62,272		
2	**Personnel**	8,267		
3	**Ship systems**	21,595		
4	**Main propulsion**	42,272		
5	**Electric power**	23,176		
6	**Payload (labour/installation)**	61,840		
7	**Variable**	0		
8	**Margins**	0		
	Sub Total	219,425		
	Design contingency margin		13,165	
	Sub Total			232,590
6	**Payload (equipment)**	57,848		
	Minor equipment margin		4,627	
	Industrial contingency margin - lack of positive data		5,784	
	Sub Total			68,261
	Sub Total			300,851
	Displacement correction		-902	
			TOTAL UPC	299,949

Table A60: Frigate Variant 3 UPC				
Group		**Cost (£k)**	**Margins (£k)**	**Total Cost (£k)**
1	**Hull**	67,504		
2	**Personnel**	8,816		
3	**Ship systems**	23,458		
4	**Main propulsion**	41,532		
5	**Electric power**	26,287		
6	**Payload (labour/installation)**	61,078		
7	**Variable**	0		
8	**Margins**	0		
	Sub Total	228,678		
	Design contingency margin		16,007	
	Sub Total			244,685
6	**Payload (equipment)**	57,848		
	Minor equipment margin		4,627	
	Industrial contingency margin - lack of positive data		5,784	
	Sub Total			68,261
	Sub Total			312,946
	Displacement correction		-4,694	
			TOTAL UPC	308,252

From above, it is clear that the light condition weight has been used in the parametric costing calculations (Equation 7) since variables and the board and growth margins do not form part of the UPC.

A13.2 TLC Analysis Data and Results

TLC Analysis Data

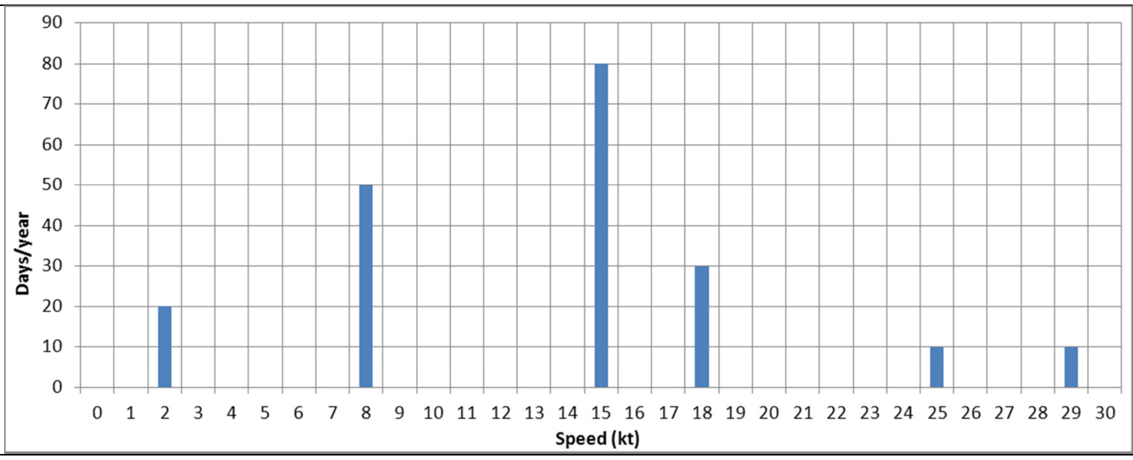


Figure A107: Operational Profile for the Three Frigate Variants

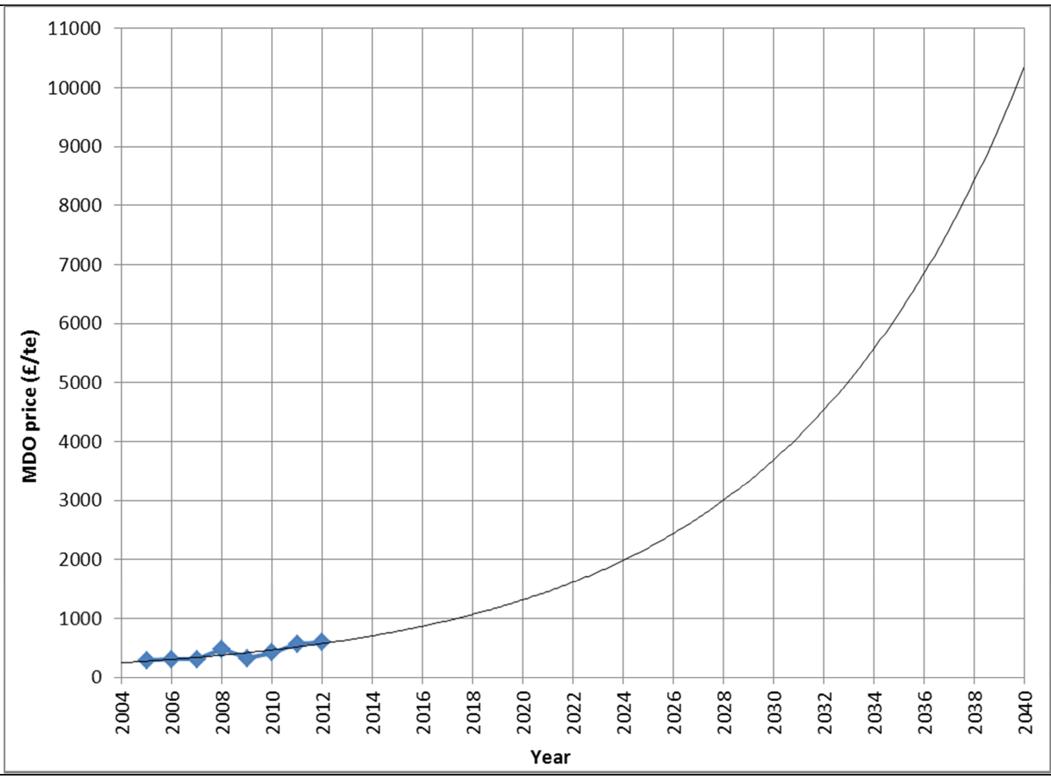


Figure A108: MDO Prices Forecast

Table A61: Salaries for the Royal Navy (UCL 2010b)

Crew	Salary (2008) (£)
Junior rates	21,000
Petty officers	30,000
Chief petty officers	35,000
Officers	41,300
Commanding officer	70,000

Table A62: Consumables Costs (UCL 2010b)	
Consumables	**Cost Per Person/day (2008) (£)**
Rations (Dry & Frozen)	8.94
Local Purchases	1.15
Miscellaneous Allowance (Quality of life)	1.5

Table A63: Annual Maintenance Cost for Selected Items of Equipment (UCL 2010b)	
Equipment Category	**Annual Expense (% of purchase cost)**
Radars and Electronics	6
Reciprocating and Rotary Machinery (compressors, pumps, engines, etc.)	1
Electrical Motors	0

All payload (i.e. group 6) equipment (purchase costs of which are found in Table A58, Table A59 and Table A60) were assumed to be in the radars and electronic equipment category of Table A63. In addition all group 3, 4 and 5 equipment, excluding electrical motors (material/equipment purchase costs of which can be found in Appendices A13.1) were assumed to belong to the reciprocating and rotary machinery equipment category of Table A63.

Table A64: Costs Incurring During Refit Periods (UCL 2010b)		
	Major Refit	**Minor Refit**
All Electronics	0	0
Mechanical Systems including Guns and Engines	15% of UPC	5% of UPC
Rest of Platform	160,000 man-hours	80,000 man-hours

Table A65: Frigate Variant 1, 2 and 3 TLC Results

		Frigate Variant 1						Frigate Variant 2						Frigate Variant 3					
Year No	Year	UPC	Fuel	Crew	Consumables	Maintenance	Refits	UPC	Fuel	Crew	Consumables	Maintenance	Refits	UPC	Fuel	Crew	Consumables	Maintenance	Refits
		(£M - 2008)						(£M - 2008)						(£M - 2008)					
0	2008	88.18						89.98						92.48					
1	2009	88.18						89.98						92.48					
2	2010	88.18						89.98						92.48					
3	2011	29.39	2.86	3.00	0.50	4.15	0.00	29.99	2.99	3.05	0.51	4.16	0.00	30.83	2.95	3.29	0.55	4.17	0.00
4	2012		2.99	2.94	0.49	4.07	0.00		3.13	3.00	0.50	4.08	0.00		3.09	3.23	0.54	4.09	0.00
5	2013		3.13	2.89	0.48	3.99	0.00		3.28	2.94	0.49	4.00	0.00		3.23	3.17	0.53	4.02	0.00
6	2014		3.27	2.83	0.47	3.92	16.69		3.43	2.88	0.48	3.93	16.96		3.38	3.11	0.52	3.94	17.33
7	2015		3.42	2.78	0.46	3.84	0.00		3.58	2.83	0.47	3.85	0.00		3.54	3.05	0.51	3.87	0.00
8	2016		3.58	2.73	0.45	3.77	0.00		3.75	2.78	0.46	3.78	0.00		3.70	2.99	0.50	3.79	0.00
9	2017		3.74	2.68	0.45	3.70	0.00		3.92	2.72	0.45	3.71	0.00		3.87	2.94	0.49	3.72	0.00
10	2018		3.92	2.63	0.44	3.63	43.08		4.10	2.67	0.44	3.64	43.82		4.05	2.88	0.48	3.65	44.85
11	2019		4.10	2.58	0.43	3.56	0.00		4.29	2.62	0.44	3.57	0.00		4.23	2.83	0.47	3.58	0.00
12	2020		4.28	2.53	0.42	3.49	0.00		4.49	2.57	0.43	3.50	0.00		4.43	2.77	0.46	3.51	0.00
13	2021		4.48	2.48	0.41	3.43	0.00		4.69	2.52	0.42	3.44	0.00		4.63	2.72	0.45	3.45	0.00
14	2022		4.69	2.43	0.41	3.36	14.33		4.91	2.48	0.41	3.37	14.56		4.84	2.67	0.44	3.38	14.88
15	2023		4.90	2.39	0.40	3.30	0.00		5.13	2.43	0.40	3.31	0.00		5.07	2.62	0.44	3.32	0.00
16	2024		5.13	2.34	0.39	3.24	0.00		5.37	2.38	0.40	3.25	0.00		5.30	2.57	0.43	3.26	0.00
17	2025		5.36	2.30	0.38	3.18	0.00		5.62	2.34	0.39	3.19	0.00		5.54	2.52	0.42	3.19	0.00
18	2026		5.61	2.26	0.38	3.12	36.99		5.87	2.30	0.38	3.13	37.63		5.80	2.48	0.41	3.13	38.51
19	2027		5.87	2.21	0.37	3.06	0.00		6.14	2.25	0.37	3.07	0.00		6.06	2.43	0.40	3.08	0.00
20	2028		6.14	2.17	0.36	3.00	0.00		6.43	2.21	0.37	3.01	0.00		6.34	2.38	0.40	3.02	0.00
21	2029		6.42	2.13	0.35	2.94	0.00		6.72	2.17	0.36	2.95	0.00		6.63	2.34	0.39	2.96	0.00
22	2030		6.71	2.09	0.35	2.89	12.30		7.03	2.13	0.35	2.90	12.50		6.94	2.29	0.38	2.90	12.78
23	2031		7.02	2.05	0.34	2.83	0.00		7.35	2.09	0.35	2.84	0.00		7.26	2.25	0.37	2.85	0.00
24	2032		7.34	2.01	0.33	2.78	0.00		7.69	2.05	0.34	2.79	0.00		7.59	2.21	0.37	2.80	0.00
25	2033		7.68	1.97	0.33	2.73	0.00		8.04	2.01	0.33	2.74	0.00		7.94	2.17	0.36	2.74	0.00
26	2034		8.03	1.94	0.32	2.68	31.76		8.41	1.97	0.33	2.68	32.31		8.30	2.13	0.35	2.69	33.07
27	2035		8.40	1.90	0.32	2.63	0.00		8.80	1.93	0.32	2.63	0.00		8.69	2.09	0.35	2.64	0.00
28	2036		8.79	1.86	0.31	2.58	0.00		9.21	1.90	0.32	2.58	0.00		9.09	2.05	0.34	2.59	0.00
29	2037		9.19	1.83	0.30	2.53	0.00		9.63	1.86	0.31	2.53	0.00		9.50	2.01	0.33	2.54	0.00
30	2038		9.62	1.79	0.30	2.48	10.57		10.07	1.83	0.30	2.49	10.74		9.94	1.97	0.33	2.49	10.97
31	2039		10.06	1.76	0.29	2.43	0.00		10.53	1.79	0.30	2.44	0.00		10.40	1.93	0.32	2.45	0.00
32	2040		10.52	1.73	0.29	2.39	0.00		11.02	1.76	0.29	2.39	0.00		10.87	1.90	0.32	2.40	0.00
Total		293.93	177.24	69.25	11.53	95.71	165.71	299.95	185.62	70.47	11.71	95.96	168.52	308.25	183.21	75.99	12.64	96.23	172.38
Total TLC							**519.44**						**532.28**						**540.45**

A13.3 WLC Analysis Results

Table A66: Frigate Variant 1, 2 and 3 WLC Results

	Frigate Variant 1				Frigate Variant 2				Frigate Variant 3			
Ship of Class	**FOC Costs**	**UPC**	**TLC**	**Disposal Costs**	**FOC Costs**	**UPC**	**TLC**	**Disposal Costs**	**FOC Costs**	**UPC**	**TLC**	**Disposal Costs**
	(£M - 2008)				**(£M - 2008)**				**(£M - 2008)**			
1	58.79	340.96	519.44	0.36	59.99	347.94	532.28	0.36	61.65	357.57	540.45	0.36
2	0.00	317.03	519.44	0.36	0.00	323.52	532.28	0.36	0.00	332.47	540.45	0.36
3	0.00	303.82	519.44	0.36	0.00	310.03	532.28	0.36	0.00	318.62	540.45	0.36
4	0.00	294.78	519.44	0.36	0.00	300.81	532.28	0.36	0.00	309.14	540.45	0.36
5	0.00	287.95	519.44	0.36	0.00	293.84	532.28	0.36	0.00	301.98	540.45	0.36
6	0.00	282.49	519.44	0.36	0.00	288.27	532.28	0.36	0.00	296.25	540.45	0.36
7	0.00	277.95	519.44	0.36	0.00	283.64	532.28	0.36	0.00	291.49	540.45	0.36
8	0.00	274.08	519.44	0.36	0.00	279.69	532.28	0.36	0.00	287.44	540.45	0.36
9	0.00	270.72	519.44	0.36	0.00	276.25	532.28	0.36	0.00	283.90	540.45	0.36
10	0.00	267.74	519.44	0.36	0.00	273.22	532.28	0.36	0.00	280.78	540.45	0.36
11	0.00	265.07	519.44	0.36	0.00	270.50	532.28	0.36	0.00	277.98	540.45	0.36
12	0.00	262.66	519.44	0.36	0.00	268.04	532.28	0.36	0.00	275.46	540.45	0.36
Total	58.79	3445.25	6233.28	4.35	59.99	3515.75	6387.31	4.35	61.65	3613.07	6485.38	4.35
Total WLC				**9741.66**				**9967.40**				**10164.46**

A14.1 Frigate Variants (Including Baseline)

Out of the six major systems modelled in the frigate design studies (for which reference should be made to the system architecture and tree diagrams included in Appendix 7 and detailed vulnerability results in the tables and charts of Section 6.3 and 6.4 and Appendix 11), Frigate Variant 1 was least vulnerable in two (forward SAM system and helicopter system), Frigate Variant 2 in one (naval gun system) and the third, trimaran, variant performed best in the remaining three (move system, ASM system and aft SAM system).

The move system of Frigate Variant 3 was invulnerable to the ASM threat investigated due to the split forward and aft propulsor configuration. The first two variants present near identical results due to the identical system configurations adopted. In fact, the move system of these two variants was only vulnerable when the same WT sections (i.e. WT sections J, K and L) were hit. In all three cases of both these design variants, it was the HTS motors and/or propeller shaft (which were located in the same WT sections) that caused the move system to be vulnerable. It is interesting to note that the power sub-system (containing all of the engines in parallel) was not vulnerable in any attack case investigated for any of the three frigate variants. The advantages of adopting an IFEP system with large distances between the power generation units and separating propulsors in a forward-aft (rather than port-starboard) configuration is thus clearly shown. A further interesting feature is the fact that after applying a linear probability hit distribution, the vulnerability of the move system in the first two frigates almost doubled. Since the move systems are vulnerable when an ASM hits occur at the aft end of the designs, by assuming a linear (as opposed to a normal) lengthwise hit probability distribution, the probability of the missile hitting the extremities of the ship designs increases.

The vulnerabilities of the naval gun system are approximately constant throughout the frigate variants due to the identical system tree diagrams and very similar equipment distribution. In all cases, the system is vulnerable when the frigate variants are hit at forward positioned WT sections B, C and D (since the magazine, gun power room, gunbay & guntrunk and the 155mm gun itself, all of which are in series, are located in WT Section C) and at the approximately amidships WT sections F and G (where the gun sensors which are in parallel, i.e. the GPEOD and surveillance radar, are affected). The slight increase of the naval gun system vulnerability in the third variant is indicative of the increased vulnerability of the forward, narrow, section of a trimaran design, where most in-series equipment of this system were located. However, it should be noted that the magazine of Frigate Variant 3 is invulnerable to any attack investigated (as opposed to the first two variants), signifying the reduced vulnerability to abovewater threats of items positioned deep in the trimaran main hull, given the increased draught. When applying a linear lengthwise hit distribution, once again an increase in the system vulnerability is observed. However, this increase is not as large as that of the move system since the naval gun system includes equipment at relatively amidships WT sections. Nonetheless, the fact that most series equipment are located at the forward extremity of the frigates leads to this slight (less than 5%) vulnerability increase.

Large variations in the vulnerabilities of the ASM systems are observed between the three frigate variants. More specifically the system vulnerabilities of Frigate Variants 2 and 3 are approximately halved when compared to the baseline, as a result of the very different equipment distributions of this system. In Frigate Variant 1, the ASM launchers and LPCR are located at amidships WT section H, which if hit leads to the greatest vulnerability of this system. The system is also vulnerable if the ship is hit at WT section G (where the LPCR and Operations Room, both in series, are affected), F (where the Operations Room is located and therefore, affected) and E (which affects the Operations Room). It should also be noted that the ASM system is marginally vulnerable when WT sections J and K are hit, due to fragments from the aft exhaust and mast affecting the aft ASM launcher. In Frigate Variant 2, a hit at amidships located WT sections E, F and G would affect the in-series Operations Room which is located at WT section F. The ASM launchers and LPCR are located aft of WT section L, which if hit leads to the largest vulnerability for this system. In addition, if WT sections K an M are hit, the ASM system is also vulnerable since the ASM LPCR is affected. Therefore, the fact that in Frigate Variant 2 the ASM in-series equipment are split between the amidships (where the control unit, i.e. Operations Room, is located) and aft (where the ASM launchers and LPCR are positioned) sections of the design, have increased the footprint of the ASM system (as opposed to the baseline frigate in which the in-series equipment are largely concentrated at amidships). One would expect that this arrangement of the ASM system items would lead to an increase in vulnerability. This however is not the case, because of the normal lengthwise hit distribution used. This significantly decreases the probability that the extremities of the ship will be hit, therefore, the vulnerability of the aft located ASM launchers and LPCR is greatly reduced, leading to the significant improvement in the ASM system vulnerability when compared to the baseline frigate. It should be noted that the ASM launchers and LPCR were located at the aft extremity of Frigate Variant 2 due to the limited amidships space resulting from the adoption of the minimal superstructure. In Frigate Variant 3 a hit at WT sections E and F was found to affect the Operations Room, located at WT section F. The Operations Rooms in the two first variants were vulnerable to missile hits at three different WT sections (i.e. the WT section at which the compartment was located and the two adjacent ones). In the trimaran variant however, the Operations Room is not vulnerable to a missile hit on the aft adjacent WT section, G, due to the shielding provided by the side hulls. The ASM launchers and LPCR are located at WT section H. The fact that the launchers are arranged in a port-starboard configuration (as opposed to the forward-aft configuration in the first two variants), made possible by the large trimaran overall beam, dramatically reduced their vulnerability given a hit at that WT section and adjacent WT section I (assuming only broadside attack). Therefore, the opportunities of equipment shielding (by the side hulls) and efficient equipment distribution (due to the large overall beam) presented by the trimaran configuration have led to a significant decrease in the vulnerability of this system. When changing the lengthwise hit distribution to a linear one, the effects are profound. The ASM vulnerabilities of Frigate Variants 1 and 3 are approximately halved since in both of these designs most ASM system related equipment is located at amidships, where the probability of being hit is greatly reduced. In the second variant, however, the vulnerability of this system is almost doubled; therefore, this design variant is now the worst performing. Evidently, this was a result of the increased ASM system footprint, which is now unaffected by the equipment location, given the constant hit probability applied to all WT sections.

Large variations are also observed in the vulnerabilities of the aft SAM system with Frigate Variant 2 presenting an improvement of almost 40% and Frigate Variant 3 of more than 80% when compared to the baseline. In all three design variants, the system is vulnerable if three aft positioned WT sections are hit. In the baseline, these WT sections are I, J (where the VLSs and LCR are located) and K. In all three cases the system is vulnerable purely because the VLSs and the LCR are affected, with the worst case being a hit at WT section J. In Frigate Variant 2, the three WT sections, which if hit resulted in the aft SAM system being vulnerable were J, K and L. The reasoning is identical to that of the baseline frigate, with the worst case being a hit at WT section K, where the VLSs and the LCR are located. It should also be noted that the aft SAM system of the second frigate variant is marginally vulnerable given a hit at WT section G. This is a result of the minimal superstructure forcing the positioning of all in parallel sensors at amidships (in WT sections F and H), with very small separation distances. A missile hit at WT section G could therefore, marginally, affect all sensors. Finally, the aft SAM system of Frigate Variant 3 is affected given a hit at WT section L, M or N. This is again caused by the vulnerability of the VLSs and LCR given a hit at those WT sections. The worst scenarios in the trimaran case occur when either WT section M (i.e. where the VLSs and LCR are situated) or N (i.e. the aft-most WT section) is hit, highlighting the increased vulnerability of equipment when placed at the narrow aft end of the trimaran. From the above facts one could deduce that the three variants should give similar aft SAM system vulnerabilities; in fact, given the increased trimaran vulnerability at its narrow extremities, it could be expected to present the worst results. However, the opposite is the case due to the normal lengthwise hit probability distribution assumed. It is clear that the VLSs and LCRs (which are almost entirely responsible for the overall system vulnerability) are positioned closer towards the aft end of the ship designs (which is less likely to be hit) from the first through to the third frigate variants and this gives significant reductions in vulnerability for the latter frigate designs. As expected, this outcome is not found when the linear hit distribution is applied. The trimaran with more vulnerable extremities now performs worst, with the overall aft SAM system vulnerability increasing by approximately nine times relative to the normal lengthwise hit distribution case. Additionally, the overall system vulnerability in the baseline frigate is slightly decreased, given that the VLSs and LCR are close to amidships which is now less likely to be hit, while in the second variant, with the aft positioned VLSs and LCR, the system vulnerability was found to slightly increased. In fact Frigate Variant 1 would appear to be the least vulnerable ship design, possibly due to the fact that the VLSs only occupy one deck (as opposed to the two decks occupied in the other two variants), with the remaining VLSs extending above 01 deck.

When considering the forward SAM system, the logic is almost identical to that for the aft SAM systems. Frigate Variants 1 and 2 output almost identical system vulnerabilities given the identical system tree diagrams and almost identical equipment distribution. With the exception of the sensor vulnerability assuming a hit at WT section G of Frigate Variant 2, detailed above, in both ship designs, the system is vulnerable given missile hits at WT sections C, D and E. The worst case, resulting to a vulnerability of 100%, is a hit at WT section D, where the systems VLSs and LCRs are located in both frigates. In the trimaran, the VLSs and LCR are located slightly closer to amidships, in WT section E; therefore, the system is vulnerable when WT sections D, E (worst case with 100% vulnerability) or F are targeted. This leads to a slight increase in the system vulnerability for the trimaran design since it is more likely to hit WT sections closer to amidships. However, this increase is to an extent counterbalanced by the side hull shielding effect given a hit at WT section F (i.e. one WT section aft of the VLSs and LCR), which is obviously not the case when the corresponding WT section, E, is hit in the monohull variants. As expected, the first two variants consistently output near identical vulnerabilities when applying the linear hit distribution, although the overall system vulnerabilities have increased by approximately 30% since it is now more probable to hit the fwd WT sections of the variants. As also expected, Frigate Variant 3 is now the least vulnerable design, presenting a reduction in the forward SAM system vulnerability of almost 30%, due to the decreased probability of the attacking missile targeting the amidships part of the frigate design.

Finally, large variations are also present in the helicopter system vulnerabilities of the three frigates. It is interesting to note that in two of the three frigate design studies (Frigate Variants 2 and 3) this is the most vulnerable system. This occurs because the helicopter system is the one containing the most in-series (unduplicated equipment), the system with the larger footprint and the helicopter is highly vulnerable to fragments from missile hits at distant WT sections. In Frigate Variant 1, the vulnerable equipment and compartments of the helicopter system are split in an aft-amidships/forward configuration, similar to the ASM system of Frigate Variant 2. Aft WT sections J, K, L and M contain items such as the AVCAT tank, magazine and weapon lift, sonobuoy store, helicopter and flight deck, all of which are in series. A hit at any one of these WT sections leads to an overall system vulnerability of over 50%. In addition, the suonoboy store located at WT section J is slightly vulnerable given a hit at WT section I. Forward and amidships WT sections C, D, E, F and G house or are adjacent to items such as the Operations Room (WT section F) and the (hull mounted) sonar instrument room (WT section D) which are in series, therefore, resulting to relatively high system vulnerabilities, between 18% and 50%. The fact, however, that the majority of the above equipment is located towards the aft end of the frigate design maintains the overall vulnerability to relatively low levels (26%). In Frigate Variant 2, the distribution of equipment and the system vulnerability given a hit between WT sections C and F is comparable to the baseline frigate. However, the AVCAT tank, magazine and weapon lift, sonobuoy store, helicopter and flight deck have been shifted approximately 3 WT sections and are now located in the aft and amidships WT sections H, I and J. It follows that a hit anywhere between WT section C and K results to a helicopter system vulnerability of over 30%. The vulnerability values are similar to those for the baseline design, however, when considering that all vulnerable items are now located in or near to amidships, which is more likely to be hit given the assumed normal lengthwise hit distribution, Frigate Variant 2 results to a more than two times more vulnerable helicopter system, highlighting possible disadvantages in the adoption of amidships flight deck configurations. As expected, the above results are no longer valid when substituting a linear lengthwise hit distribution, which results to an approximately 50% more vulnerable system for Frigate Variant 1, and 40% less vulnerable for Frigate Variant 2. Both designs now output near identical system vulnerabilities, with the baseline frigate performing slightly worse, possibly due to the increased system footprint. The equipment distribution of the helicopter system in the trimaran variant is similar to that of Frigate Variant 2, with a flight deck located close to amidships. Any missile hit between amidships WT sections D and L (between which all vulnerable equipment are located), result to the overall system being vulnerable. However, the increase in vulnerability compared to the baseline frigate is only approximately 35%. This is due to the shielding effect of the side hulls to equipment located near the centreline, such as the Operations Room and the weapon lift, and the invulnerability of items located deep in the hull, such as the sonar instrument room, the magazine and the AVCAT tank. Therefore, when applying a linear lengthwise hit distribution the helicopter system of the trimaran frigate design is the least vulnerable; decreasing by approximately 15%, it is now more than 20% less vulnerable than the baseline design. It is interesting to note that when using the linear hit distribution, the helicopter system is the most vulnerable of the modelled systems in all frigate designs.

After normalising the system vulnerabilities and applying the weightings proposed by 1st Lt. Fonseca, the least overall vulnerable ship was found to be the trimaran variants followed by the baseline and the most vulnerable ship design was the second variant. Although after analysing the individual system vulnerabilities this was expected, what was not expected is the very large margin by which the trimaran design performs better (presenting an approximately 60% decrease in overall vulnerability compared to the baseline). This, however, can easily be understood after investigating the applied weighting scheme. The move major system (which was the only major system to be invulnerable to the assumed threat, but solely in Frigate Variant 3) was given a weighting larger than the sum of the weightings of the remaining major systems. This amplified the difference between the vulnerability performance of the trimaran and the other two design variants. Frigate Variant 2 is approximately 15% more vulnerable than the baseline, which has mainly resulted from its exceptionally vulnerable helicopter system. When changing the lengthwise probability hit distribution, the overall vulnerability of the three frigate design variants is practically unchanged, although the individual system vulnerabilities present vast variations. The trimaran variant still presents an improved performance of approximately 60%, for which its invulnerably move system is almost entirely responsible. The second frigate variant is slightly better performing, but still approximately 12% more vulnerable than the baseline. Although the vulnerability of the helicopter system is now comparable to that of the baseline, it is observed that the increased vulnerability of the ASM system maintains the second variant as the worst performing in terms of vulnerability.

After carrying out the sensitivity tests on the applied major system weighting scheme, by using the weighting schemes proposed by the RN officers at Dstl for the three scenarios summarised in Section 6.4.1, the main conclusion was that ship vulnerability is more sensitive to the ship design than to the weighting scheme or the operational scenario. In all examined cases, Frigate Variant 3 was the least vulnerable design, followed by Frigate Variants 1 and 2. However, the differences between the vulnerability performances of the three variants have been altered. When considering scenarios 2 and 3 (and the weighting schemes proposed by the RN staff), Frigate Variant 2 produces consistent results with those outputted when using 1st Lt. Fonseca’s weighting scheme. The second variant is between 6% and 26% more vulnerable than the baseline. However, when examining scenario 1, this margin increases to between 25% and 35%. This is a direct result of the comparatively large weighting given to the helicopter system by all RN officers for scenario 1, due to the presence of a submarine threat (not present in the other two scenarios), highlighting once again the poor performance of the amidships helicopter system of that design variant. A further point of interest is the fact that the vulnerability performance improvement of the trimaran variant, when compared to the baseline, is between 28% and 42% (when considering all scenarios and the corresponding weighting schemed proposed by the RN staff) as opposed to the approximately 60% improvement previously observed. This is a result of the comparatively (to the move major system) much higher weightings given to the fight major systems by the RN officers. Therefore, the augmentation of the margin between the trimaran and the baseline designs (due to the invulnerable trimaran move system) was lessened. The small weightings given to the fight major systems by 1st Lt. Fonseca are not surprising since an operational scenario was not proposed.

A14.2 Corvette, Baseline Frigate and Destroyer

Out of the six major systems modelled in the ship size and level of combat system and ship performance capability varied combatants (for which reference should be made to the system architecture and tree diagrams included in Appendix 7 and detailed vulnerability results in the tables and charts of Section 6.3 and 6.4 and Appendix 11), the Corvette design was least vulnerable in two (move system and aft SAM system) and most vulnerable in the remaining, Frigate Variant 1 was not the least vulnerable in any and the Destroyer design performed best in the remaining four (naval gun system, ASM system, forward SAM system and helicopter system).

The move system of the Corvette design was invulnerable to the ASM threat investigated for the exact same reason as with the trimaran frigate variant, i.e. due to the split forward and aft propulsor configuration. The propulsor arrangement in the baseline frigate and Destroyer design is identical. This leads to the result that the move systems in the two combatants are only vulnerable when the second, third and fourth aft-most WT sections (i.e. J, K and L in the frigate and K, L, M in the Destroyer) are hit, due to the HTS motors and/or propeller shaft (which are located in the same WT sections) being affected. However, the move system of the Destroyer is less vulnerable by approximately 35%. This could be attributed to the larger volumetric size of the three above WT sections (since the Destroyer has a larger beam and is deeper due the greater number of decks) which could more easily contain the blast and fragmentation damage caused by the exploding ASM warhead, therefore, decreasing the vulnerability of the motors and propeller shafts. As in the three frigate design studies, the power sub-system (containing all of the engines in parallel) was not vulnerable in any attack case due to the widely separated IFEP system selected.

Large variations are observed in the vulnerabilities of the naval gun system, despite the similar system tree diagrams and equipment distributions. In all three designs, the system is vulnerable given a hit in any of five WT sections (A, B, C, D and E in the Corvette; B, C, D, F and G in the baseline frigate and B, C, D, E and F in the Destroyer); i.e. the WT sections in which, or adjacent to which, are located the in-series magazine, gun power room/LCR, gunbay & guntrunk, gun, or gun sensors. However, the average naval gun system vulnerability of the five above WT sections is generally smaller for the Destroyer (49%); followed by the baseline frigate (54%) and the Corvette design (62%). As mentioned above, this is partially due to the larger volumetric size of the WT sections in the larger ship designs, which could more easily contain the blast and fragmentation damage caused by the exploding ASM warhead and therefore, decrease the equipment vulnerability. In addition, an important difference between the system tree diagrams for the three ship designs is the fact that the Destroyer includes more naval gun sensors (forward and aft MFR, which are widely separated, and GPEOD, located at the forward mast together with the forward MFR) as opposed to the surveillance radar and GPEOD, both located on the forward mast, of the Corvette and frigate designs. This dramatically reduces the gun sensor vulnerability, affecting the average system vulnerability of the five WT sections mentioned above. Furthermore, the fact that the number of WT section is dependent on ship size (the Corvette has 9 WT section, the baseline frigate 13 and the Destroyer 14) increases the system footprint, as a proportion of ship length, and therefore, the probability of the system being affected by a constant threat. The five WT sections which if hit would cause the naval gun system to be vulnerable have a 65% chance of being targeted by the attacking missile in the Corvette, 41% in the baseline frigate and 24% in the Destroyer. Note that these percentages are also affected by the location of the WT sections, given that a normal lengthwise probability hit distribution was assumed. Inevitably, given a constant (five WT section) system vulnerability footprint, the smaller in length ships would include more of those WT sections towards amidships, therefore, further increasing the probability of these WT sections being hit. The two above observations have resulted to the Corvette having a more than two times more vulnerable naval gun system than the baseline frigate, and the Destroyer presenting an improvement of almost 60%.

Large variations between the three combatants are also present in the vulnerability performance of the ASM systems. However, these variations are almost exclusively caused by the probability of the attacking missile hitting the WT sections which cause that system to be vulnerable. The ASM system tree diagrams in all three combatants are similar as is the distribution of equipment for this system, mainly concentrated at the amidships section of the ship designs. All three combatant designs have a vulnerability footprint of four WT sections (C, D, E and F in the Corvette design and E, F, G and H in the baseline frigate and Destroyer), i.e. the WT sections in which, or adjacent to which, are located the in-series Operations Room and ASM LPCR and launchers. (Although, as mentioned in Appendix 14.1, the baseline frigate ASM system is negligibly vulnerable when WT sections J and K are hit, due to fragments from the aft exhaust and mast affecting the aft ASM launcher). Unlike the move and naval gun system, the average vulnerability of the ASM system, given a hit in any one of the four above WT sections, is approximately equal (50%) for all ship designs. This could be attributed to the fact that the ASM launchers are positioned abovedecks (in the Corvette and Destroyer) therefore, the internal volumetric size of the WT section is inconsequential; moreover, the longer length of the Destroyer leads to a less cluttered weatherdeck, therefore, the ASM launchers are more prone to fragmentation damage from the masts and exhausts. However the proportionally (to the ship overall length) larger vulnerability footprint of ASM system in the smaller ship designs has led to the probability the four WT sections (forming the vulnerability footprint) being hit equal to over 80% in the Corvette design and approximately 60% in the baseline frigate and 50% in the Destroyer. These differences are almost entirely responsible for the almost 40% more vulnerable Corvette ASM system and 15% less vulnerable Destroyer ASM system, compared to the baseline frigate. In should be mentioned that the ASM system is the most vulnerable of the six major ship systems modelled in all three combatants, due to the concentration of the vulnerable equipment items in the amidships (therefore, most likely to hit) sections of the ships.

Regarding the aft SAM system, the Corvette design outputs the best performing results. The system tree diagram and equipment distribution between the Corvette and baseline frigate designs are very similar, the only main difference being a shift of the VLSs and LCR one WT section aft in the Corvette. In this ship design, due to the lack of space, the VLSs were fitted port and starboard of the hangar. Both ship designs have a vulnerability footprint of 3 WT sections (G, H, F and I, J, K respectively), i.e. the WT sections in which, and in proximity to which, the in-series VLSs and LCR are located. (Although it should be noted that the aft SAM system of the Corvette is marginally vulnerable given a hit at WT section E due to fragment effects from the forward mast and exhaust damaging the VLSs). However, the fact that in the Corvette design, the vulnerable VLSs and LCR are located one WT section aft when compared to the baseline frigate (and are therefore less likely to be targeted given the normal hit distribution), leads to a reduction in the system vulnerability of almost 25%. The Destroyer design adopted a different, more capable, SAM system, with a different system tree diagram. The aft SAM system LCR is not in series, but in parallel to the Operations Room, making the aft SAM control sub-system invulnerable to a single missile attack. In addition, the larger volumetric size of the Destroyers WT sections, previously mentioned, have decreased the vulnerability footprint of the VLSs to two WT sections, J (where the VLSs are located) and K (which if hit results to a marginal VLS vulnerability). One could thus expect the Destroyer aft SAM system to perform best with a great margin, however, this is not the case. The system is less than 10% less vulnerable than the corresponding baseline frigate system and therefore, more vulnerable than the Corvette corresponding system. This is attributed to two actualities. First, the Destroyers VLSs were located in a WT section closer towards amidships, due to the comfortable layout arrangements resulting from the larger dimensions, increasing the probability of that WT section being targeted. Second, the different SAM systems chosen for the combatants could operate with different sensors. The MBDA MICA PDMS of the Corvette and baseline frigate could operate with six sensors in total (forward and aft navigation radar, forward and aft IRST, surveillance radar and ESM/ECM module) while the PAAMS ADMS of the Destroyer could only operates with the two MFRs. (In fact, two single faced array MFR Spectars was opted over one two faced array MFR Sampson, included in the Type 45 Destroyer, since it would be futile to design a split forward and aft VLS system, with a single system sensor). The consequence was for the aft SAM sensors sub-system to be vulnerable (although marginally) given a hit at any WT section between WT section F an K, therefore, increasing the vulnerability footprint of the system to six WT sections, larger than the corresponding footprints in the two smaller combatants.

Similarly to the aft SAM system, the system tree diagram and equipment distribution between of the forward SAM system of the Corvette and baseline frigate designs are very similar. The only main difference is a shift of the VLSs and LCR one WT section forward in the Corvette design, due to the lack of space. Both ship designs have a three WT section vulnerability footprint (B, C and D in the Corvette and C, D and E in the baseline frigate), i.e. the WT section in which, and adjacent to which, the VLSs and LCR are located. The system vulnerability values given a hit at the WT section containing the VLSs and LCR (C and D respectively), or the WT section forward of the former, are similar in both combatant designs. However, a missile hit at the aft adjacent WT section to the one housing the VLSs and LCR results to an almost halved system vulnerability in the Corvette design, compared to the baseline frigate. This is possibly because, the aforementioned WT section, (i.e. WT section D in the Corvette) includes superstructure (conversely to the corresponding WT section, E, in the frigate design), therefore, obstructing fragmentation damage to the vulnerable VLSs and LCR. However, the forward SAM system of the Corvette is nevertheless almost 50% more vulnerable overall, compared to the baseline frigate, purely because of the proportionately (to the designs overall length) larger vulnerability footprint (and although the vulnerable system equipment is located one WT section closer to the designs extremity). This results to a 37% probability of one of the three WT sections forming the vulnerability footprint being hit in the Corvette design, as opposed to the corresponding 18% in the baseline frigate design. As previously mentioned, the Destroyer includes a different SAM system. As with the aft SAM system, the vulnerability footprint of the VLSs of the Destroyers forward SAM system spans across two WT sections, E (where the VLSs are located) and F. In addition, the vulnerability footprint of the fwd (being identical to the aft) SAM sensors sub-system spans across WT sections F to K. However, with the exception of the WT section in which the VLSs are located, E, a missile hit to any other of the above WT sections results to a relatively small overall system vulnerability, and the hit probability of WT section E is under 7%. This overweighs the effects of the larger vulnerability footprint and results to the Destroyer presenting the least vulnerable forward SAM system, almost 40% less vulnerable than the baseline frigate design.

The approximate aft-amidships/forward configuration in which the vulnerable equipment and compartments of the helicopter system are split in Frigate Variant 1 was detailed in Appendix 14.1. A similar configuration is observed in the Corvette design. When hit, aft WT sections G, H and F result to a system vulnerability of 100%, since they contain items such as the AVCAT tank, magazine and weapon lift, sonobuoy store, helicopter and flight deck, all of which are in series. Forward and amidships WT sections B, C, D and E result to system vulnerabilities between 22% and 82% if hit, as they house or are adjacent to items such as the Operations Room (WT section D) and the (hull mounted) sonar instrument room (WT section B) which are also in series. Thus, the cramped Corvette design has a smaller vulnerability footprint of seven WT sections, compared to the 10 WT sections of the baseline frigate. However, as a proportion of the total number of WT sections in the two designs, both combatant designs have an almost identical footprint (78% and 77% respectively), resulting to an almost identical probability that one of the WT sections forming the vulnerability footprint would be hit (77% and 80% respectively). However, the Corvettes helicopter system is approximately 40% more vulnerable as a result of the larger average system vulnerability, given a missile hit in one of the above WT sections (72% and 51% respectively). As mentioned before, this is probably an outcome of the smaller volumetric size of the WT sections in the smaller ship design, which could not contain the blast and fragmentation damage caused by the exploding ASM warhead as efficiently as a larger WT section. In the Destroyer design, the systems vulnerable equipment was split in an aft-amidships-forward configuration. A hit in either WT sections L, M or N, resulted to a system vulnerability of at least 62%, since they contain items such as the AVCAT tank, magazine and weapon lift, sonobuoy store, helicopter and flight deck, all of which are in series. Amidships WT section F contained the Operations Room, also in series, therefore, a hit to that or either adjacent WT sections resulted to a system vulnerability between of 37% and 67%. Fwd WT section B included the, in-series, (hull mounted) sonar instrument room, and if that or the aft adjacent WT sections were hit, system vulnerability values between 31% and 58% resulted. It is also interesting to note that when WT section H is hit, fragmentation damage from the amidships mast marginally damages the in-series sonobuoy store; moreover, a hit at WT section K causes damage to the magazine (located in the aft adjacent WT section) and the helicopter, from fragmentation of the aft mast and exhaust. As a result, the vulnerability footprint of the helicopter system is equal to that of the baseline frigate in terms of number of WT sections, but proportionately smaller, due to the larger size of the ship. This has led to a slight decrease in the Destroyer's helicopter system vulnerability by approximately 10%.

After normalising the system vulnerabilities and applying the weightings proposed by 1st Lt. Fonseca, the least overall vulnerable ship design was the larger Destroyer (approximately 30% less vulnerable than the baseline frigate) unsurprisingly, since it outputted the lowest vulnerabilities for four out of the six modelled major ship systems. However, despite the fact that the smaller Corvette design was the worst performing in four of the major systems, it was still overall less vulnerable than the baseline frigate, in fact, almost identical to the Destroyer design. This was a direct result of the unproportionally higher weighting applied to the move system (compared to the five Fight systems), which was invulnerable in the Corvette, as analysed above. If a weighting of 2, rather than 9 was used for the move system (i.e. in agreement with the weightings proposed by 1st Lt. Fonseca for the Fight systems, Table 4.1), the Destroyer design would continue to be approximately 30% less vulnerable than the baseline frigate, but the Corvette design would now be the most vulnerable ship design, by approximately 20% compared to Frigate Variant 1. Thus, contrasting the conclusions made in Appendix 14.1 regarding the insensitivity of the frigate variants overall vulnerability to the weighting scheme used, it is now realised that this is not always the case, implying that more research is necessary in the application of appropriate weighting schemes and their association to operational scenarios.

A brief sensitivity test was carried out on the Destroyer design, in order to examine the effect of changing the elevation and azimuth angles of the attacking missile impact vector (as opposed to constantly assuming broadside attacks at 0^o elevation). A general system vulnerability pattern was observed, i.e. in most cases, the helicopter system was the most vulnerable, followed by the ASM system, the move system, the naval gun system, the aft SAM system and finally the forward SAM system. Although it is beyond the scope of this project to in depth analyse the reasoning behind this pattern, it is easily understood that it relates to factors such as the vulnerability footprint of the system and the location of system equipment and compartments. However, in all system cases, vulnerability result fluctuations of over 50% were observed, depending on the missile angle of attack. This indicates that not only is there currently a vast variety of threats which have to be assessed and against which modern naval ships must be designed (as mentioned in Section 7.1.4), but that the effects of each threat largely depend on factors such as the hit location and weapon trajectory. This clearly increases the challenges of both survivability assessment and survivable ship design.

A14.3 AOR Variants

Out of the seven major systems/capabilities modelled in the two AOR variants (for which reference should be made to the system architecture and tree diagrams included in Appendix 7 and detailed vulnerability results in the tables and charts of Section 6.3 and Appendix 11), the first variant was least vulnerable in one (move system) and the second variant performed best in five (all RAS related capabilities and aviation support). The CIWS of both designs was invulnerable.

The move system of AOR Variant 1 is invulnerable owing to the vastly separated MMRs (by eight WT sections, once again highlighting the survivability related advantages of IFEP) and propulsor units (separated by eleven WT sections, between the aft pods and forward pumpjet). Note that the pumpjet was purely fitted (in the forward MMR) in order to take advantage of this large separation distance between the ships engines since it would be futile to design a vastly split forward and aft power system, with all propulsors concentrated in the same ship section. The different configuration adopted in AOR Variant 2, dictated the positioning of both MMRs towards the aft end of the ship design, separated by one WT section. Therefore, the need for a forward propulsor was no longer conceived, resulting solely to the double aft mounted pod configuration. Despite the compact MMR arrangement, no single ASM hit affected the power sub-system in AOR Variant 2. Rather, it was the in-series and unduplicated pod drive room which caused the move system to be vulnerable when hit at the two aft-most

WT sections. As evident from the system tree diagrams, the inclusion of the forward pumpjet in the first AOR variant meant that the pod drive room was no longer in series since the pumpjet could be controlled through other ship compartments (SCC and bridge), whereas each pod required an operational pod drive room to be properly functioning. Therefore, as wrongly conceived, the absence of a forward propulsion unit (i.e. duplicated and separated propulsion) in the second variant indeed resulted to a vulnerable move system (against the given threat). However, the system vulnerability was maintained at exceptionally low levels (less than 1% vulnerable) due to the location of the vulnerable WT sections at the aft extremity of the design, leading to extremely low hit probabilities.

The capability to RAS liquids in AOR Variant 2 is invulnerable to any single attack by the given ASM. In contrast, the above capability is vulnerable in AOR Variant 1 only when the attacking missile hits WT section E, i.e. when the in-series bridge, located in that WT section, is targeted. The bridge is necessary in all RAS operations to provide ship handling. The presence of a single aft superstructure block in AOR variant 2 has led to the (approximately amidships) RASco having an unobstructed view towards the ship's bow (as opposed to the RASco of the first AOR variant, located amidships, between the two superstructure blocks). Therefore, ship handling can be facilitated through either the bridge or the RASco in that design variant; the bridge is no longer in series but in parallel with the RASco. The ship handling sub-system in AOR variant 2 is invulnerable to any single ASM attack, once again highlighting the advantages of duplication and separation of identical functions. However, the overall vulnerability of the RAS liquid capabilities of AOR Variant 1 are maintained at low levels (approximately 1%) due to the small vulnerability footprint, comprised of only one (out of a total of seventeen) WT section, and the small probability of the attacking missile hitting that forward located WT section (approximately 4%). It should be noted that both RAS liquid capabilities contain an, in-series, either AVCAT/dieso cargo sub-system, which in turn contain in parallel the liquid cargo tanks of each WT section. The split of the liquid cargo tanks (and, therefore, pumps) in an approximate aft-forward configuration in both ships has led to the invulnerability of the either AVCAT/dieso cargo sub-system.

In both AOR Variants, the capability to RAS solids is vulnerable when the two adjacent WT sections that contain the solid cargo stores and lifts are hit (i.e. WT sections J and K in AOR Variant 1 and G and H in AOR Variant 2). Similarly to the RAS liquid capabilities, in both designs the RAS solid capabilities contain an in-series either ordnance cargo and lift sub-system. This sub-system contains two further (in parallel) sub-systems each consisting of the solid cargo stores and lift in either of the two WT section. Both of these parallel sub-systems are only vulnerable when either of the two WT sections above is hit. It should be noted that stores below No 6 Deck (i.e. ordnance stores) are invulnerable to the abovewater ASM threat assumed; however, the vulnerability of the cargo lift which extends through to the weatherdeck has led to both RAS solid capabilities (dry stores and ordnance) outputting identical vulnerability values in each ship design. It is thus the grouping of all solid cargo stores and lifts in adjacent WT sections that has led to the vulnerability of these capabilities; although stores and lifts are duplicated, they are merely separated by one WT bulkhead. As mentioned in Appendix 2.3 and Section 5.3 this arrangement was selected to minimise required routes for RAS operations with hazardous materials. AOR Variant 2 has almost 40% more vulnerably RAS solid capabilities for two reasons, the first being the ship handling argument analysed above. The second is that in AOR Variants 2, the two WT sections comprising the vulnerable footprint are positioned slightly forward of amidships (as opposed to the amidships positioned corresponding WT sections in AOR Variant 1) leading to a smaller hit probability (22% versus 27% for either WT section in the two variants) due to the normal lengthwise hit distribution assumed. It is interesting to note that in AOR Variant 2, the RAS solid capabilities are the most vulnerable of the capabilities/systems modelled.

When considering the aviation support system, AOR Variant 1 outputs an almost two times more vulnerable system than its counterpart, this being the most vulnerable system of the first variant. Given a missile hit anywhere between WT section L and Q, both auxiliary designs output almost identical vulnerability results. In both designs, WT sections M to Q contain in-series items such as the flight deck, hangar, ships own AVCAT tank and all aviation workshops; moreover, a hit at WT section L affects the adjacently located hangar (and in AOR Variant 2, marginally affects the either navigation radar sub-system since the two navigation radars are not separated by as much as in the first variant, given the single superstructure block). However, in AOR variant 1, the aviation support system is also vulnerable given a missile hit at WT sections I, J and K. This is a result of fragmentation damage (possibly from the RAS posts) to the items listed above. Such fragmentation damage is not observed in AOR Variant 2 due to the fact that the aviation facilities listed above are shielded by the additional superstructure in WT section L and the additional (02 and 03) decks in the aft superstructure. In this single superstructure block design, the aft positioned superstructure had to be enlarged in order to house all required compartments and systems. This has had the obvious effect of providing further protection to the aviation support system concentrated at the aft end in both ship designs.

Finally regarding the CIWS, both variants output invulnerable results. In both designs, the system is duplicated, through the inclusion of two SeaRAM launchers, each with an independent sensors and control room, and separated by nine and eleven WT sections respectively. The only further sub-system in the CIWS is the power sub-system, demonstrated to be invulnerable to any single ASM attack in both variants. This outcome not only confirms the promising results of a duplication and separation philosophy, but also highlights the vulnerability reduction advantages of independent systems with simple hierarchical relationships.

After normalising the system vulnerabilities and applying the weightings proposed by RN officer (rtd.), Lt. Cdr. Day, AOR Variant 2 proved to be approximately 40% less vulnerable than the first variant. This was expected and is mainly caused by the entirely invulnerable RAS liquid capabilities, both of which were given maximum weighting. The fact that AOR Variant 1 possessed an invulnerable move system (also given maximum weighting) maintained the vulnerability difference between the two designs at the above level. AOR variant 2 was also less vulnerable in the RAS solid capabilities and aviation support system. However, the fact that the vulnerability differences in these systems were not as large, between the two variants, and the relatively small weightings given to them, meant that they did not influence the total vulnerability results to a great extent. In fact, if the vulnerabilities of the move system and RAS liquid capabilities were equalised in the two ship designs, AOR Variant 2 would only output approximately 10% less overall vulnerability results.

When comparing the auxiliary ship designs with the combatant designs it is clear that the AORs generally output smaller system vulnerability values, possibly due to their significantly larger size (although different systems with different architectures and tree diagrams were modelled in the two ship types).