Twin Variant Naval Ship Concept Design

Imran Khan
Pakistan Navy, Islamabad, Pakistan
ik_6451@yahoo.com

***Abstract*— The warships are designed over a period of 2 to 5 years. The sister ships may continue to be built up to 15 years from the class ship (first of a kind) getting into service, with little design modifications and improvements. The requirement of a common hull design has emerged, more important than ever, in light of worldwide trend of curtailing defense budgets and increasing focus to extract maximum out of a single design through modular approach. Utilizing modular concept a single optimized hull will be designed; and the two variants will have a major difference of a plug only. The types of hullform considered are both conventional and unconventional. The common capabilities, payload and space arrangement are similar on both variant V1 & V2. Major advantages of a common hull design are reduced design & build costs, ease of personnel training, ease of maintenance and common support infrastructure including inventory management. Though the commonality of hull forms and system architecture will add design and build complexity, the advantages to be gained are numerous. The enhanced capabilities and payload are provided in V1 through addition of a plug, whereas the low end V2 variant is envisaged to have a high export potential due to marginally low cost.**

I. PREAMBLE

This paper presents a concept design of Twin Variant Naval Ship (TVNS) which will fulfil a greater number of more challenging and diverse roles than previous generation warships. Two variants are expected; V1 – a high-end, conventional capability multi-mission variant, and V2 – a smaller, versatile, flexibly configured escort vessel. The work has been undertaken at University College London (UCL) during Ship Design exercise by a group comprising of Naval Architects and Marine Engineers.

The TVNS project offers a lucrative "one size fits all" solution which seemingly attractive is inevitably prone to growth, leading to cost escalation. The requirement for "V2" to be a more economic small scale design, with possible export potential when compared to its high end high capability sister "V1" offers a significant challenge, particularly with such an emphasis is placed on commonality of design. The two possible solutions initially considered are:

i. A common hull for both V1 and V2, expected to be the best possible solution. Advantages to such a strategy include, massively reduced development and manufacturing costs. However these are gained at the expense of either lower design efficiency in the V2 variant or reduced capability in V1.

ii. The other approach would be two completely independent designs, with commonality achieved in the system fits. The result is two efficient designs with appropriate higher capabilities but at a significantly higher build and development cost, thus lesser possible savings. This would result in a reduced V1 batch and possible cancellation of V2 project, as budgets escalate.

With the resultant outcome of these two scenarios, an alternative was required somewhere between the two extremes. The anticipated solution is an optimised V1 design with a common bow and stern section as of V2, but with an additional midsection for V1 capability-specific fit. With careful design, bow and stern sections can be designed identical for both V1 and V2 variants with no compromise in V2 hull form. This will have reduced costs specifically for V2 as design and manufacturing processes will be common. Such a technique has already been proven successful but in reverse on the Royal Navy 'Stretch' Type 42 [4] where an additional section was added during design to increase capability.

Whilst it is not suggested that such a solution is perfect, however it offers many advantages over the more traditional alternatives. Few design compromises will have to be made in the V2 variant, compared to V1, but these would be comfortably outweighed by the cost reductions enjoyed as a result of commonality of sections.

II. REQUIRED CAPABILITIES

A. Role

Based on Concepts of Operations for each TVNS set of capabilities as a result are shown in Table I:

TABLE I. – ROLE/CAPABILITY

	V1 – Warfare Combatant	V2 – Stabilization Combatant
Power Projection Ashore	Land attack, shore bombardment and support to tactical amphibious landings via Naval Gunfire Support (NGS) and long range land attack	Support small-scale stabilisation operations via Naval Gunfire Support (NGS) Possibility of medium range land attack missile installation
Sea Control	Fleet or independent capability, speciliasing in ASW with self-defence against significant AAW threats, adept in littoral environment	Conduct sea line protections and chock points escort operations with self-defence against AAW threats, adept in the littoral environment
Mine Clearance	Undertaken mine countermeasures activities in support of the fleet	Undertaken mine countermeasures activities in support of the fleet
Naval Presence	Provide flexible response and naval presence in areas where there is little support including self-deployment, or contribution to large task forces	Provide flexible response and naval presence in areas where there is little support, or contribution to large task forces

978-1-4673-9127-6/16/$31.00 ©2016 IEEE

III. MONOHULL OR A TRIMARAN HULLFROM

In the early part of the design stage various unconventional hullforms like surface effect ships and multihulls were considered for the TVNS; and only Trimaran proved to be a feasible alternative to Monohull. Other authors have also considered Tirmaran as the only alternate option [19, 20]. A quick analysis was undertaken to decide on the preferable option. A Trimaran has advantages at higher speed, when the wave making resistance is dominant form of resistance and attains greater speeds for relatively less power compared to a Monohull. Conversely, at lower speeds when the skin friction is dominant form of resistance, the Monohull offers superior performance due lesser wetted surface area. An analysis for the operating profile of TVNS vs speed requirements is presented in "Fig. 1" below:

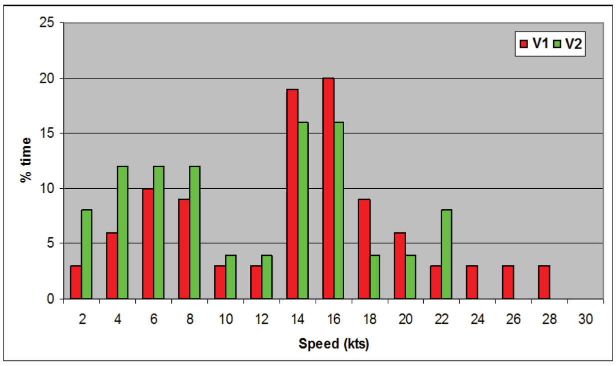

Figure 1. Operating Profile

It is evident that the ship is expected to spend the majority of its life at cruise speed, so the possible fuel savings at high speeds for a Trimaran would be greatly offset by fuel savings at cusing speed. Another disadvantage with the Trimaran layout is that the central hull has a relatively small beam for the size of the ship. This would make squeezing of large machinery into the small lower decks difficult.

However, a Trimaran due its outriggers has benefits over Monohull, like better seakeeping characteristics, a larger flight deck, capability to operate at comparatively severe seastates and a more stable platform for undertaking UXV (Unmanned Vehicles) operations. A large flight deck may even allow the potential for having 2 helicopters onboard which could increase the capability significantly.

A major factor in the decision of having a Monohull is due to the concept of having a common hull with a section/ plug cut out. It is deemed that the UPC (unit procurement cost) benefit from having a common hull would not be achieved if a Trimaran hullform is used. Moreover, the V2 variant is required to have a high export potential, and is likely that a Trimaran may not attract many customers due the increased risk of unconventional hullform and a higher UPC.

IV. INITIAL SIZING & WEIGHTS

In order to determine the size of vessel, the UCL Ship Design Procedure [1] along with UCL Ship Data Book [2] is consulted. To get a first estimate for the weight and volume of the ship, a payload-volume fraction of 0.16 [2] a ship density of 0.3 [2] is used, based on built warships data. The first estimate are shown in Table II:

TABLE II. FIRST SIZE ESTIMATES

Enclosed Volume	18400 m^3
Weight	5520 Tonnes

From these initial estimates, the iterative procedure for each weight group is carried out by use of the following regression formulae [1]:

$$Vol_{Net} = Vol_{Gross} - (Vol_{Mcy} + Vol_{Fuel\ Tanks}). \quad (1)$$

Based on preliminary power requirements of approximately 30MW the machinery room total volume is estimated to be as 2750m^3, and required tank volume of 1120m^3 based on perceived endurance of 9000Nm; and is found in sync with previous warships data.

The growth margins are also applied from Def Stan 109 Part 1 [3] as 0.65% per annum based on a 10 year major refit cycle resulting in a growth margin on 6.69%. As the design is based around a flexible modular design the ship has potential for increase in weight and volume as addition fittings are made.

After detailed working the improved size and volume estimates are as shown in Table III:

TABLE III. SHIP FIRST SIZE ESTIMATES

Enclosed Volume	22599 m^3
Weight	6048 Tonnes

These estimates are relatively higher than the first estimates, as the TVNS concept proposed has a large mission bay; hence a larger volume than a typical frigate. The group wise distribution of weight for Surface Combatant V1 and V2, refined through the interactive process of design cycle is is illustrated in Table IV and shown in "Fig. 2" below:

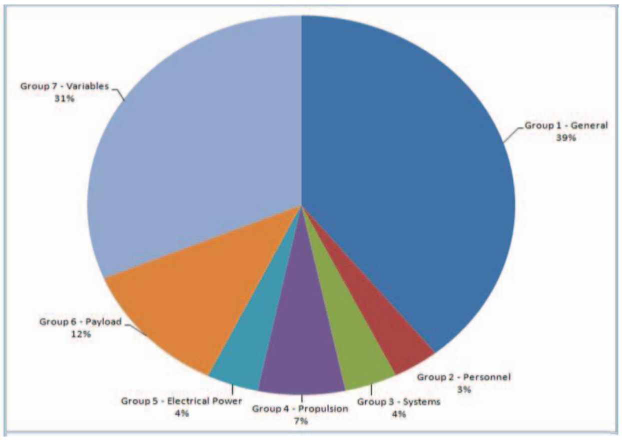

Figure 2. Weight Breakdown – V1

TABLE IV. SUMMARY OF WEIGHT FOR V1 & V2

Weight Group	Weight – V1	Weight – V2
Group 1 – Hull	2092	1929
Group 2 – Personnel	187	148
Group 3 – Ship Systems	212	194
Group 4 – Main Propulsion	352	307
Group 5 – Electric Power	208	189
Group 6 – Payload	614.5	253.5
Group 7 – Variable Load	1669.5	1471.5
Growth Margin	563	527
Design Margin	150	135
Total Weight (E.O.L.)	6048	5154

Moreover, a summary of various conditions for V1 and V2 is listed below in Table V:-

TABLE V. DIFFERENT LOADING CONDITIONS

Loading Condition	Weight – V1	Weight – V2
	(Tonnes)	(Tonnes)
Light	3822	3858
Light Harbour Return	4675	4027
Deep End of Life	6185	5298

V. INVESTIGATION OF PAYLOAD OPTIONS

The choice of payload greatly influences the cost, sizing and layout of the final design. Following payloads are identified for the design (Table VI):

TABLE VI. SELECTED PAYLOADS

Capability	V1	V2
Airborne	√	√
Anti Submarine Warfare (ASW)	√	√
Land Attack	√	X
Gunfire Support (NGS)	√	√
Anti-Air Warfare (AAW)	√	√
Close In Weapon System (CIWS)	√	√
Mission Bay Loaded Equipment	√	√
Radar / Sensor Fit	√	√

Increasingly warship capability demands are being met with the use of unmanned vehicles (UXVs) particularly with modern navies. This trend is indicative of the type of future naval operations to be expected and is the reason for the inclusion of a large functional mission bay, included in both V1 and V2 solution. Every effort is made throughout the design process to accommodate and optimise the vessel for the operational use of UXVs and this is reflected in their prominence in the chosen payload.

An overview of the options and considerations attached to each payload group is discussed below followed by a cost benefit analysis for both variants.

A. Airborne Capability

There is an inherent requirement for an organic air capability, ranging from the ability to land helicopters on a flight deck in order to simply refuelling and rearming them through to supporting multiple air platforms and UAVs in a workshop within hangar. LYNX has been considered however the more capable and larger MERLIN EH101 has been finalized, with additional ability to land troop through CHINOOK onto the flight deck to embark EMF. Whereas a FIRESCOUT UAV is selected. It is intended that V2 will carry the same airborne capability as that of V1.

B. ASW

An essential part of antisubmarine operations is the sonar fit with bow sonar being critical for passive torpedo warning and mine detection but less useful for submarine detection particularly at range, the choice then lies between a dedicated towed array or a helicopter deployed dipping sonar.

The towed array system offers excellent performance in both deep and littoral waters and has passive and active capabilities. However towed arrays require significant transom and quarter deck space and restrict ship operations whilst in use.

Whereas the more lightweight, helicopter deployed, dipping sonar offers advantages in its flexibility of deployment and its space requirements. However, by its nature its limited by organic helicopter's other operational requirements. Moreover, deep water submarine detection is limited by the length of cable required to penetrate the thermocline, and time the helicopter can spend on station. Therefore, helicopter dropped sono buoys are also included for tracking identified threats over longer time frames.

In terms of prosecution of threats the most practical option is aerial launched torpedoes from either helicopter or UXV, allowing targets well outside the range of any ship launched system to be attacked. This is particularly useful in an escort style role where multiple vessels are being protected. For close in defence a STINGRAY torpedo with associated system will be installed.

C. AAW

A defensive anti air capability is adopted as opposed to offensive. The choice is wither a deck launched system with minimal below deck space requirements alongwith lower range or a silo launched system with a larger range but significant weight and volume requirements.

It is important to have flexibility built into system and produce a future proof design. In this regard deck mounted launch systems are usually missile specific, however they are relatively cheap to replace as newer systems are developed. Conversely silo launchers can support a multitude of missile options and upgrades but are significantly more expensive to replace.

In view of defensive anti air capability requirement and to keep the cost lower specifically for V2, deck launched SeaRAM is selected instead of silo launched counterparts.

D. Land Attack

A long range land attack capability is required for V1 but not of V2, and hence lesser cost restraints are imposed on choice.

Energy weapons under development were also considered, but not acceded due their excessive cost, limited data availability and unproven platform performance. Moreover, they would require significant power requirements; that would drive the cost and design of the ship.

Helicopter launched systems was considered as a low cost option, but was dropped due helicopters lesser availability (other operational engagements), range restrictions and vulnerability of helicopter in a combat environment.

Whereas a more conventional silo launched long range missile system with tomahawk or harpoon offers a more de-risked solution despite imposing large weight and volume requirements. Moreover, the system also offers advantage of launching a plethora of missiles launched from a standard silo. Furthermore, there is a possibility of launching AAW and land attack from a common silo, with possible overall reduced cost and/ or allowing the ship to be fitted with mission specific missiles.

E. NGS

Options for Naval Gunfire Support are more restricted than those for other areas, with the main drivers being commonality across designs. Considered options are Vickers 114mm and Vickers 155mm with the main differences being reduced range and cost. The latter option of 155mm gun is preferred, with a possibility of fitting a customer's choice gun to an export version of the V2.

F. CIWS

Close in weapon systems are subject to change as technology advances and so for that reason a preferred approach is to select a proven system with minimal through deck requirements that may be replaced easily in the future and to allow volume in the superstructure for any future CIWS requirements. Possible options are the PHALANX and GOALKEEPER designs. Phalanx a widely employed CIWS is preferred, against the more capable Goalkeeper option which is however expensive and requires significant through deck penetrations.

G. Radar Fit

The radar fit is instrumental in supporting many of the activities of the V1 and V2. It is required to support command and control and missile firing operations of the platform. For V1 multi phased array radar such as the MFRAPR or SAMPSON (as of Type 45) is considered, which offers a high command and control capability, multiple targets tracking and a superior range. This is delivered at a significantly higher cost both in terms of UPC and through life, and is significantly heavy. Whereas for the V2 to be a cheaper export version a conventional medium range Surveillance and Threat Alert Radar (STAR) either in single or dual face configuration, representing a cheap and proven design choice is chosen.

H. Mission Bay

The mission bay represents the core of the TVNS capability, allowing the design to adapt to a large variety of tasks by carrying the relevant equipment. Specifically options are considered to fulfil the mine and countermeasures (MCM) and embarked military force (EMF) requirements, alongwith airborne UXV capability for a variety of tasks. The large mission bay is also present in the V2 variant, so as to allow for the possibility of increased capability at minimal extra platform cost.

MCM

Baseline options include the use of tethered ROV systems such as the SEAFOX providing a proven and low cost capability, used purely on their own such systems may be impractical as they would require close proximity to mine threats; a high risk scenario for a high cost, high capability platform.

EMF

The number of EMF and accordingly the number of RHIBs required to deliver them to shore is also a decision point. A minimum capability is considered to comprise of 15 EMF alongwith their stores and a mission bay volume for one RHIB. Or a top end capability comprising of 30-40 EMF and two RHIBs.

VI. PAYLOAD COST BENEFIT ASSESSMENT

To undertake cost benefit assessment of payloads, Equity3 ® Software is used, to finalize payload selection. It is a Multi-Criteria Decision Analysis (MCDA) tool that assists in obtaining better value-for-money when allocating limited resources and budgets.

Each area listed in the above section is weighted against its relevance towards a capability, within each area and each option (ranging from baseline to high end) is weighted representing its contribution (benefit) towards the area. Costs are entered appropriately [2]; where exact prices are unknown indicative values are chosen from experience and intuition. For the cases where equipment costs are not applied to the UPC of the vessel e.g. in the case of embarked aircraft or UXVs, the estimated cost of the required volume and weight on the structure as well as any support required is still applied

MCDA models are constructed for both V1 and V2 variants, producing cost benefit envelopes. Ideally a solution should be chosen from the frontier at a knuckle – the point at which the gradient of the line decreases significantly, as visible in "Fig. 3, 4". This area represents a point beyond which smaller gains in capability are obtained for larger gains in cost. This is of particular importance in the V2 variant where export price is a large driver. Cost Benefit envelopes and baseline and optimum payload fits are seen outlined below for both variants:

A. V1 Variant Analysis

Considered V1 options are seen below in Table VII, all areas are mutually exclusive aside from the sonar system which is seen to be cumulative. The cost of options get high from left to right across the table. Baseline options are coloured as green and blue while optimized options are coloured as yellow and blue i.e. blue are common. The MCD analysis is presented in "Fig. 3" where the resulting baseline (green circle) and optimized fit (yellow circle) are clearly identifiable.

TABLE VII. V1 - OPTIONS

Land Attack	8xHarpoon	16xHarpoon	8xTomahawk	16xTomahawk		
NGS	114mm	155mm				
AAW	2xRAM	8xSeawolf	8xSeasparrow	16xSeasparrow	32xSeasparrow	
CIWS	1xPhalanx	1xGoalkeeper	2xPhalanx	2xGoalkeeper	3xPhalanx	4xPhalanx
Small Fire	2x20mm	2x40mm	4x20mm	4x40mm		
Radar	SR STAR Single Face	SR STAR Double Face	MFRAPAR	Samson		
MCM	Divers	Seafox ROV	Seafox ROV and USV	Full UXV System		
EMF	15xEMF (1xRHIB)	30xEMF (2xRHIB)				
Sonar System	No Sonar	Merlin	Spherion	Towed Array		
Airborne Group	1xLynx	2xLynx	Merlin	Merlin & UAV	2xMerlin	2xMerlin & UAV

TABLE VIII. V2- OPTIONS

NGS	114mm	155mm				
AAW	2xRAM	8xSeawolf	8xSeasparrow	16xSeasparrow	32xSeasparrow	
CIWS	1xPhalanx	1xGoalkeeper	2xPhalanx	2xGoalkeeper	3xPhalanx	4xPhalanx
Small Fire	2x 20mm	2x 40mm	4x20mm	4x40mm		
Radar	SR STAR Single Face	SR STAR Double Face	MFRAPAR	Samson		
MCM	Divers	Seafox ROV	Seafox ROV and USV	Full UXV System		
EMF	15xEMF (1xRHIB)	30xEMF (2xRHIB)				
SonarSystem	No Sonar	Merlin	Spherion	Towed Array		
Airborne Group	1xLynx	2xLynx	Merlin	Merlin & UAV	2xMerlin	2xMerlin & UAV

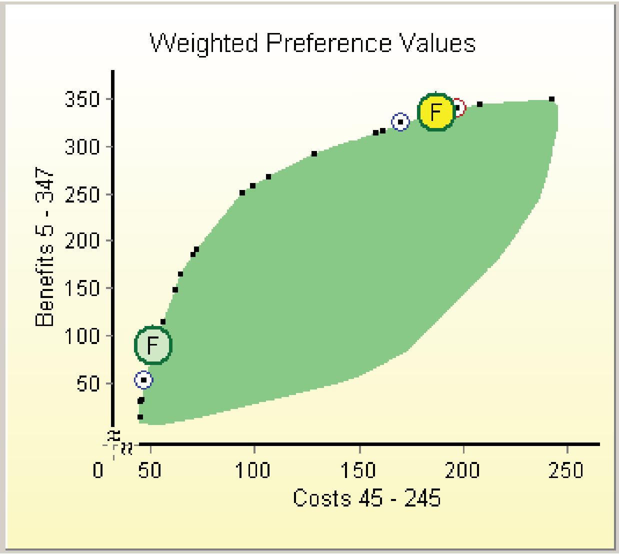

Figure 3. V1 MCD Analysis

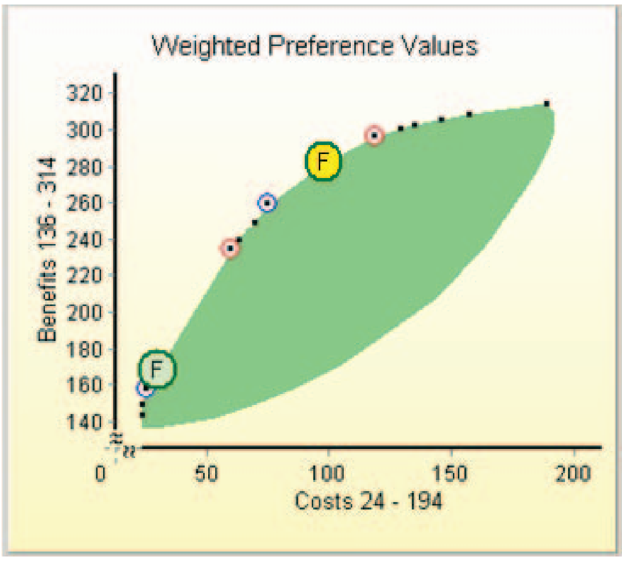

Figure 4. V2 MCD Analysis

The upper line of the envelope represents the solution frontier, from this it can be seen that the V1 baseline falls below the knuckle point. So the optimum solution not at the ideal position, is heavily influenced by the requirement for both a towed array and MFRAPAR both of which are high cost, high volume additions.

The V1's position as a high end, high capability platform however means this added cost is taken as a necessity. Interestingly the addition of a silo is seen as cost effective in that both land attack and air defence capabilities can be provided from a common piece of equipment despite its weight and impact on the superstructure.

B. *V2 Analysis*

Analysis of the V2 variant is carried out in the same manner as for V1. The difference being that Land Attack has been omitted. All benefit estimates are reworked as a group to reflect the change in role. Baseline and Optimised payload fits coloured as green and blue while optimized options coloured as yellow and blue i.e. blue are common are seen in Table VIII.

As with V1, the V2 variant baseline design falls well below the knuckle of the envelope and so is significantly below the optimum configuration, as seen in "Fig. 4". The full capability design is seen to be much closer to the knuckle than either of the V1 solutions illustrating its position as a cost effective export variant with a lower capability. The point exactly on the knuckle represents the same design but with a dual face STAR radar; this option is decided as without a reasonably high end radar V2 variant would lose attractiveness on the export market.

VII. PARAMETRIC SURVEY

Having achieved a weight and volume balance and a selected payload from previous sections, the hull parameters can be determined by conducting a parametric survey. The aim of the survey is to determine the effects of varying different parameters affecting the shape of the ship while remaining within the specified dimensional constraints and performance aspects.

The parametric survey is split into 2 parts. The major parametric survey undertaken in order to find the effect of hull depth, length and superstructure proportions. While the minor parametric survey is used to aid the selection of Cb and Cp.

A. *Limitations on parameters:*

Length:

An important aspect of the high-capability TVNS design is the weapons and sensors fit each with associated requirement of deck area and deck clearance. From these upper deck layout considerations, a V1 upper deck length of 135m is required In addition to the space requirement, a length to depth ratio of 14:1 is not to be exceeded to avoid structural weight penalties [1].

Beam:

As with the length, there is a requirement for the beam to be at least 16m in order to provide for an adequate flight deck for helicopter operations and sufficient space for the launch and recovery of UAVs.

Depth:

In order to fit in all the required equipment into the vessel a minimum of 4 deck layout is decided. Additionally, an outer bottom depth of 1.5m is desired for fuel storage, in order to meet the extended range requirements. Allowing for a 2.7m minimum deck height a minimum depth of 12.3m is required, but a deck height of 3m is desired in order to make the ship more comfortable for personnel onboard. Moreover, minimum freeboard requirement for torpedo launching of 4.5m is also considered throughout the parametric survey process.

B. *Major Parametric Survey*

In the initial stage of the major parametric survey the length is varied alogwith the depth for different beams. In view of the constraints outlined above a design envelope is formed which will reveal results for varying superstructure proportions. At this stage following parameters are assumed and plot seen in "Fig. 5" is developed:

a. Superstructure Proportion - 0.20
b. Block Coefficient - 0.50
c. Prismatic Coefficient - 0.62

As can be seen from "Fig. 5", the design envelope limits the design to a 4 deck layout, however the desired 3m deck height can be achieved as shown by the lower horizontal line (orange colour) which shows an allowable length from 125m to 130m. The results of the major parametric survey are summarised in Table IX:

TABLE IX. MAJOR PARAMETRIC SURVEY – PARAMETERS

Length (WL)	130m
Beam	16m
Depth	13.5m
Double Bottom Height	1.5m
Number of Decks	4
Superstructure Proportion	0.2
Deck Height	3m
Draught	6.1m
Length/Depth ratio	9.62

However, further analysis is required in order to choose a length.

C. *Constraints*

GM Required:

Using empirical formulae [5] it is possible to calculate the minimum GM required in order to avoid having stability issues later in the design process. For the ship density of 0.26kg/m^3 found in the weight balancing, and a depth of 13.5m; the outcome of GM requirement is approximately 1.55m.

Length:

As found from the previous plot, the length range over which possible permutation are allowed is 125m to 130m.

Superstructure Proportion:

The superstructure proportion (Vs) is limited to a minimum of 0.2. This limit is based on minimum requirements based on similar ships to this concept design. The plot of constraints can be seen in "Fig. 6".

The results of the survey show that the design envelope is restrictive with regards to the superstructure proportion. The optimal design solution is chosen as one which had the longest length and the largest superstructure proportion. This point corresponds to a waterline length of 130m and a superstructure proportion of 0.2.

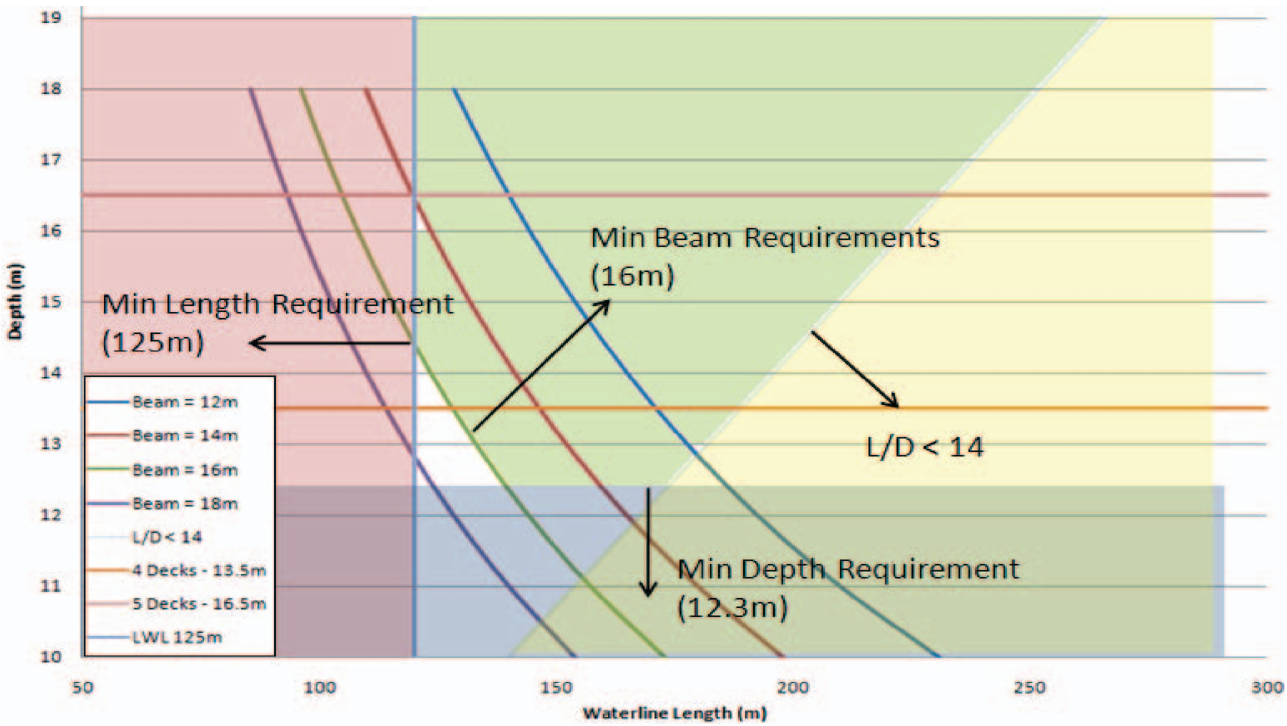

Figure 5. Major Parametric survey plot

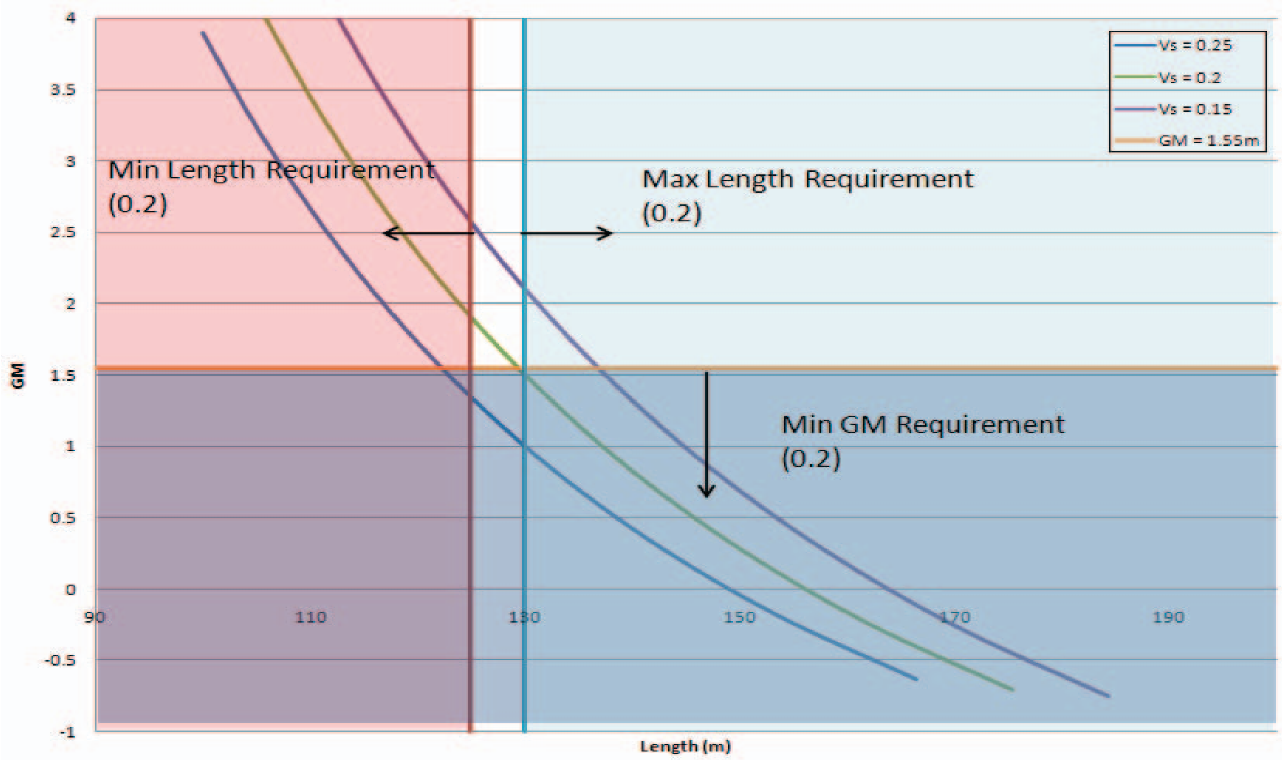

Figure 6. Superstructure constraint plot

D. Minor Parametric Survey

The results from the major parametric survey are brought forward into the minor parametric survey and used to determine the hull form parameters. The plot of varying the prismatic coefficient and the block coefficient showing the effect on vessel length is shown “Fig. 7”.

In the major parametric survey it is found that the desired waterline length is 130m. There are allowable hull form parameters on the vertical line from this length. A lower Cp would result in the ship being finer and consequently have lower wave-making resistance which is beneficial for fuel efficiency and top speed capabilities. However, fuel tank capacity in the outer bottom is limited drastically if the prismatic coefficient is too low. Following parameters as defined in Table X are chosen:

TABLE X. MINOR PARAMETRIC SURVEY - PARAMETERS

Cp	0.62
Cb	0.47
Cm	0.758

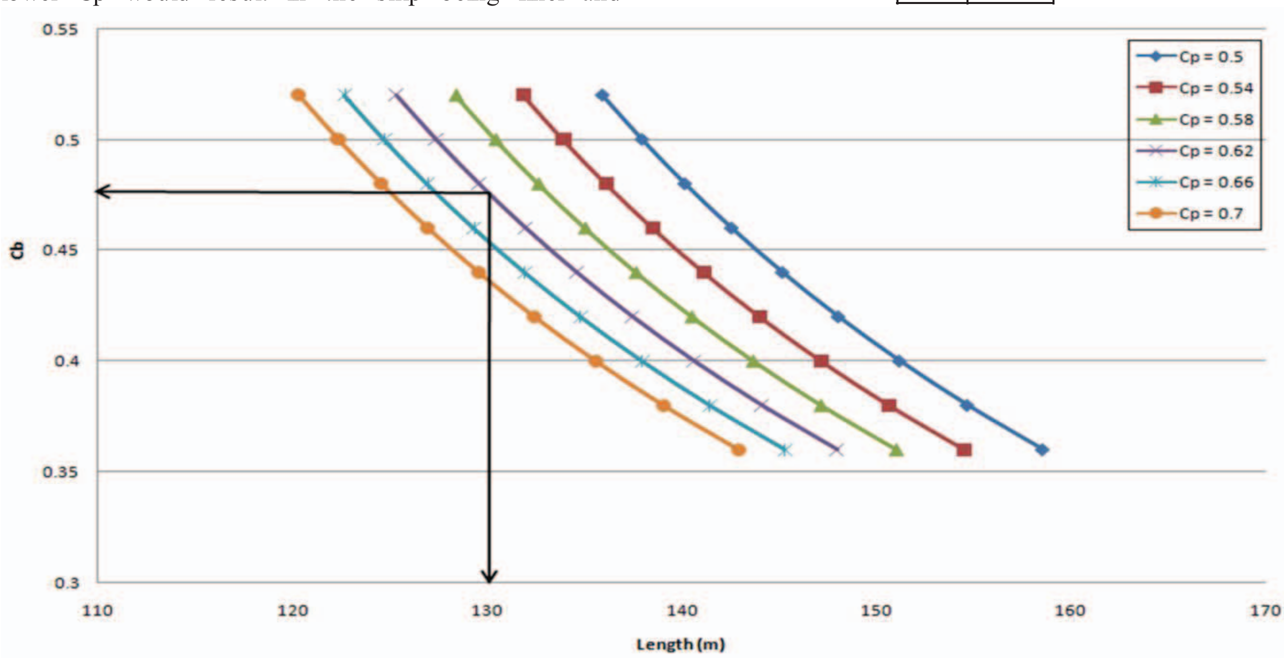

Figure 7. Minor Parametric survey plot

E. Finalized parameters

After detailed parametric sensitivity analysis finalized parameters of both variants are appended in Table XI:

TABLE XI. FINALIZED PARAMETERS OF BOTH VARIANTS

	V1	V2
Displacement	6048 te	5235 te
Total Internal Volume	22599m^3	17683m^3
LBP / LOA	130m / 140m	120m / 130m
Beam (waterline)	16.5m	16.5m
Depth	13.5m	13.5m
Draught	5.74m	5.66m

VIII. PRIME MOVER

All options for propulsion were initially considered, including nuclear propulsion [21], Integrated Fully Integrated Electric Propulsion (IFEP) and direct drive gas turbines or diesels, which were then evaluated through a sensitivity study for following criteria:

a. Cost – both Through Life and Purchase
b. Space & Weight
c. Fuel economy
d. Vulnerability
e. Noise signature
f. Technological risk
g. Emissions
h. Reliability, Availability and Maintainability

The weighting of each category was adjusted to reflect the differing priorities of each variant. The high capability V1 required a high emphasis on vulnerability and noise signature, whereas V2 prioritised cost and fuel economy. Both variants attached high importance to Reliability, Availability and Maintainability for an IFEP. The sensitivity study conducted indicates that IFEP provides the best propulsion solution evaluated against the criteria considered.

A. IFEP

The selected mode of propulsion, IFEP has an increased UPC and weight which is offset by significant advantages in fuel economy, vulnerability and noise signature; all considered key tenets of the design for both variants. IFEP also presents the added advantage of flexibility in prime mover selection, which is particularly suitable for the V1/ V2 concept, given the export requirements of V2. The absence of long shaftlines and complex gearing arrangements further enhances the ease of a modular build strategy.

B. PRIME MOVER

A number of prime mover options are available with an IFEP system. Primarily, generation can be achieved via the use of a combination of diesel engines and gas turbines to drive generators. In general, gas turbines offer a higher power to weight ratio but a significantly lower fuel economy than diesel engines.

Based on a total installed power requirement derived from the top speed and service load requirements, prime movers were sized to suit a generation capacity of around 40-45MW for the V1 variant. Following two combinations were assessed:

a. 1xRolls Royce WR-21 21.5MW Gas Turbine + 2xWartsila 8L26 2.6MW Diesel Gen-set
b. 1xRolls-Royce MT-30 36MW Gas Turbine + 3xWartsila 8L26 2.6MW Diesel Gen-set

A number of prime movers were considered and selection was primarily based on fuel economy and prime mover loading. "Fig. 8" below shows the fuel consumption data for above two combinations:

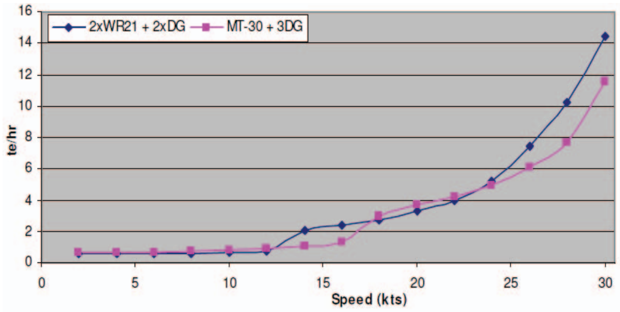

Figure 8. Prime Mover Fuel Consumption Comparison

The combination using just one gas turbine and three diesel generators shows a clear advantage in fuel economy at cruise and top speed, and consequently consumes 80% less fuel annually than the configuration with two gas turbines. This factor, combined with optimum prime mover loading across all speeds led to the selection of the 1 MT-30 and 3 Diesel Generator configuration.

The selections explained above are for the V1 variant, however to maintain commonality between V1 and V2 the principal propulsion configuration (1 gas turbine + 3 diesel engines) would remain the same for V2. However, for the reduced power requirement of V2 a smaller gas turbine like 9.45MW Solar Mars-90 will be utilized, whilst delivering good efficiency and reliability similar to the Rolls Royce MT-30. This will keep commonality between V1 and V2 higher by maintaining the same configuration within the engine room, and simply replacing the prime mover.

The V2 variant will have a flexible propulsion configuration to maximise export potential ie an all diesel variant can also be offered with significant fuel cost reductions, but limiting the top speed to 19 knots. Nevertheless, this is expected to present an attractive export option for clients lacking in gas turbine operating expertise.

C. MOTOR

To meet the top speed requirements of each variant, V1 will require two 16MW motors while V2 needs two 8MW motors. Four motor types are considered

a. Advanced Induction Motor (AIM)
b. Permanent Magnet Motors (PMM)
c. High Temperature Superconducting (HTS)
d. The DC Advanced Propulsion Motor

HTS wire and cooling technology is now sufficiently mature to permit commercial development of motors. The HTS motor offers a higher efficiency than the AIM at around 97.5%, and a very high power density [8]. At similar power ratings, the HTS is some 30% to 40% smaller than the AIM. However, The HTS requires a closed loop liquid helium cooling system to maintain the motor windings at less than 32K, and also presents very high purchase costs due to the expense of superconducting magnet wire.

The advantages of a Permanent Magnet Motor (PMM) also include high power and torque density, and reduced weight and size compared to a conventional induction motor [9]. However, the immaturity of this technology combined with concerns over the inability to turn off the magnetic field under fault conditions make this also an unsuitable choice for the TVNS.

The Advanced Propulsion Motor (APM) is based upon Active Stator Technology, employing essentially a brushless DC machine with a solid state commutator. In an Active Stator machine, the principal magnetic field is established on the rotor using a shaft mounted exciter and rotating diode assembly. The design maximises power density so that the whole machine, including the equivalent of the inverter bridges, occupies approximately 50% less volume than an equivalent AIM. The APM could be run of a full DC system, and promises higher power density and efficiency than an equivalent HV AC and AIM system. This is a promising avenue for development, but once again the use of such immature technology is considered unviable.

The Advanced Induction Motor, built by Converteam, has a robust, mature design and a proven record of operational use in the commercial and military sector. The AIM has an inherently simple mechanical structure, and hence inherently high reliability and shock withstand capability; AIM designs have already been qualified to US Navy and Royal Navy standards [7]. This makes it the logical choice for V1 and V2.

IX. PROPULSOR

The selection of an IFEP (Integrated Full Electrical Propulsion) means that that there a number of propulsor options:

a. Fixed Pitch Propellors (FPP)
b. Controllable Pitch Propellors (CPP)
c. Podded drives (Azimuthing and Fixed)
d. Waterjets

Podded propulsion presents a number of advantages: motors can be accommodated outside the hull, allowing a flexible machinery room arrangement and removing the shafting, pods offer excellent manoeuvrability at slow speeds. Commercially, the option is attractive as it allows for the purchase cost of the motor to be delayed until a late stage of the project when it can be "bolted" on to the hull. There are, however, concerns regarding the ability of the bearings to withstand shock, particularly important for a naval vessel designed to undertake mine countermeasures duties. Furthermore, faults in the pods could impose reliance on dry-docking for repairs and maintenance, which again is undesirable for a military vessel.

It was decided to discount pods, as the potential increase in manoeuvrability was not deemed a driving requirement for this vessel. Naval vessels are likely to take tugs when coming alongside, whether they are fitted with pods or not.

Although waterjets can offer high propulsive efficiencies at speeds greater than 25-30 knots, the operating profile of both variants dictates that the majority of time will be spent at cruise speeds between 12 and 18 knots. At such speeds, waterjets are much less efficient than conventional propellers, and would generate much more radiated noise. Waterjets were therefore discounted.

Fixed pitch propellers were the obvious solution for this vessel. The variable speed drive configuration proposed enables accurate control of torque and speed across the propeller speed range, and the ability to reverse direction of rotation, so the increased cost and complexity of a controllable pitch system was not required in this case.

A. *Geometric Restrictions*

Preliminary considerations when choosing a prop for the given hull form are purely geometric, namely determining the maximum diameter prop that has sufficient clearance from the side when alongside, from a dock floor when docking down, from the hull when underway and from the neighbouring propeller. These restrictions are seen illustrated below in "Fig. 9":

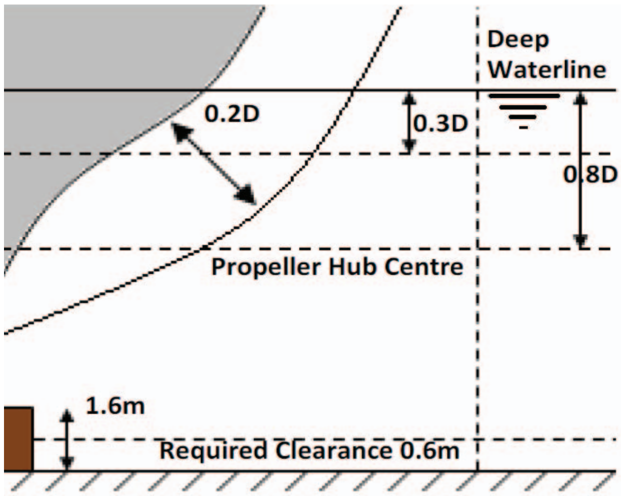

Figure 9. Geometric Considerations

A standard 5 bladed design has been considered, with tip clearance greater than or equal to diameter (D) divided by number of blades ie a minimum blade clearance of 0.2D is assumed [1]. A relationship between draft and maximum prop diameter can then be formed as such:

$$D = T - 0.3D + 1. \tag{2}$$

With a draft of 5.8m this equates to a maximum prop diameter of **5.2m** from geometric considerations.

B. *Physical Restrictions*

Unfortunately a further restriction is present that has not yet been examined in the geometric considerations. The fact that a two prop design is chosen means the arrangement of the prime mover, Advanced Induction Motors (AIMs), must be examined to ensure they fit within the machinery space in the PARAMARINE® model. Moreover, a similar problem was confronted concerning the vertical positioning of the machinery space assigned to the AIMs. If the shafts extend horizontally the propellers intersect the hull at the top of the after cut up. The cut up cannot be raised as it is limited due to the deck height in the mission bay above it; resultantly the shafts and AIMs have to be raked.

Information provided by the UCL design office is examined to determine the effect of changing rake on local prop efficiency in the form of cavitation inception speed this data is presented in Table XII. Shaft Rakes beyond 10^0 are considered unacceptable with zero rake predictably offering the best characteristics. Through manipulating the PARAMARINE® model and trial and error it is possible to fit the propellers satisfactorily by implementing a shaft rake of 4^0.

TABLE XII. CAVITATION ONSET FOR VARYING RAKE

Shaft Angle (^{0})	Cavitation Onset Speed (Kn)	
	Tip Vortex	Face
0	18	-
5	14	20
10	12.5	16.75
15	11.5	16

Now considering the lateral spacing, space on the tank top deck is limited and to have better lateral spacing the AIMs are raised slightly into the wider section of the deck. Maximising this separation and considering the allowable tip clearance between propellers; the maximum propeller size defined by the hull is 4.6m. A graphical depiction of this arrangement can be seen in "Fig. 10" below:

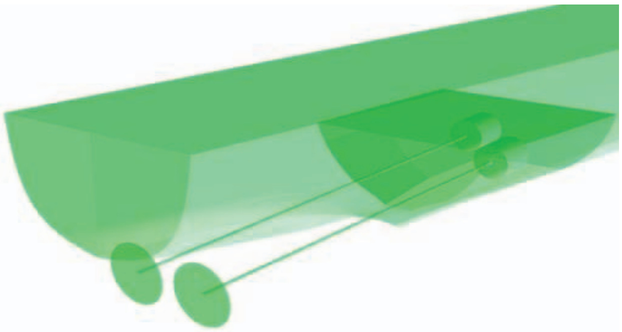

Figure 10. PARAMARINE® - Propulsion Layout Model

C. *Powering Requirement Calculations*

With maximum propeller diameter defined a preliminary propeller selection is carried using, the Wageningen B series, with data from UCL design data [2]. This uses advance coefficient (J), Pitch Diameter Ratio (P/D) and Expanded Blade Area Ratio (Ae/Ao) to find values of Kt and Kq (using the Oosterveld and Van Oossaren method). The spreadsheet [6] for calculations takes shaft power and motor rpm as inputs as well as Taylor wake fraction (Wt) and thrust deduction factor (t). The required shaft power obtained from a simple Holtrop and Mennon calculation alongwith desired rpm is appended in Table XIII:

TABLE XIII. V1 AND V2 POWERING REQUIREMENTS

	V1		V2	
	Sprint (28kn)	Cruise (14kn)	Sprint (22kn)	Cruise (14kn)
Rt (kN)	1249.71	186.60	983.64	162.21
RPM	200	95	180	80

With these values and using the spreadsheet mentioned above, a variety of different diameters are trialled until a satisfactory efficiency is obtained; around 0.7. Moreover, this analysis is also conducted to achieve required sprint speed. Matching is carried out by balancing values of Ae/Ao from the cavitation check against values input into the initial calculation until minimum variation between the two exists. The resulting propeller has following characteristics:

a. Blades – 05
b. Diameter – 4.571 m
c. Ae/Ao – 0.879
d. Open Water Efficiency (sprint) – 0.690
e. n (sprint) – 205 rpm
f. Open Water Efficiency (cruise) – 0.674
g. n (cruise) – 96 rpm

D. *Resistance Estimates*

All resistance estimates are carried out using the 'full' Holtrop and Mennon method by spreadsheet [6]. Input are estimates of resistance at varying ship speeds as well as propeller sizing details; while outputs are plots of shaft power in conventional operation, a trailing or locked shaft as seen in "Fig. 11".

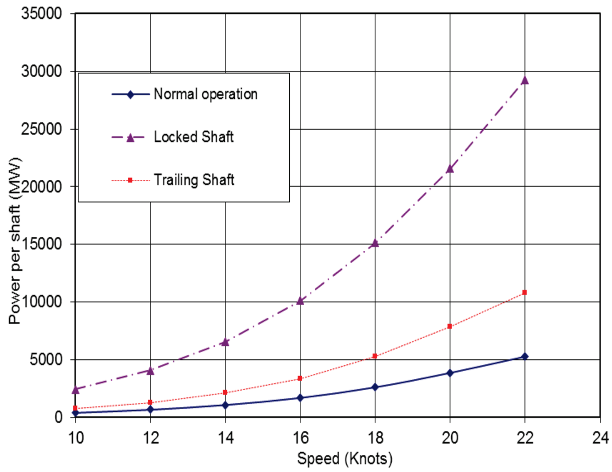

Figure 11. V1 Shaft Power predictions

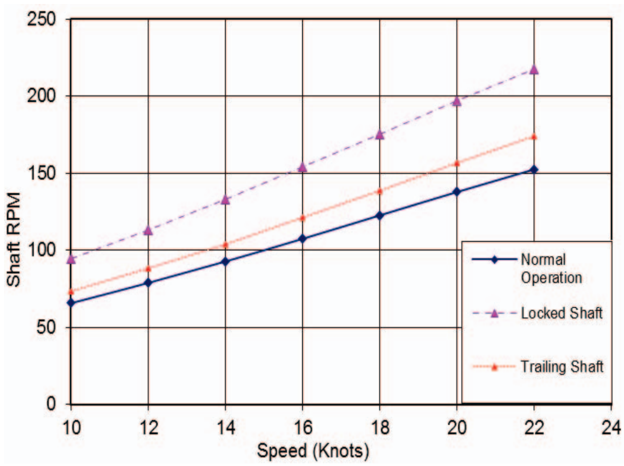

Figure 12. : V1 Shaft RPM predictions

Similarly plots are produced for shaft revolutions and propeller efficiencies, as seen in "Fig. 12" and "Fig. 13" respectively. The propeller efficiency is seen to lie close to the required level of 0.7 and shaft revolutions stays around 200 rpm, as required, except in the locked shaft case; which is evident.

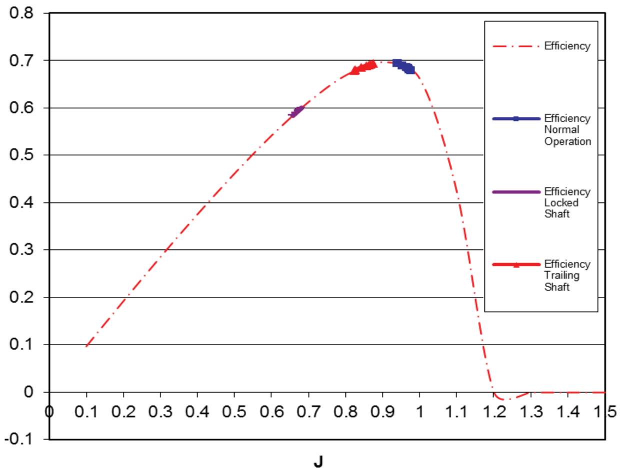

Figure 13. V1 Propeller Characteristics

X. HULL FORM

A. Form Parameters

A representative model is generated in PARAMARINE® with values of waterline length, beam and form parameters calculated from initial sizing and parametric surveys. The process of hull creation is iterative, and the basic hull shape is formed from a series of NURB style lines referred to as xt-curves in PARAMARINE®.

The main consideration during creation of geometry is the inclusion of a silo section, removable for the V2 variant, visible in "Fig. 14". It is located within a parallel section of hull near amidships, so that its removal has minimal effect on vessel lines and form; both in an aesthetic and practical sense. The positioning of the silo section has a minimal effect, on longitudinal centre of buoyancy and resistance, of both variants.

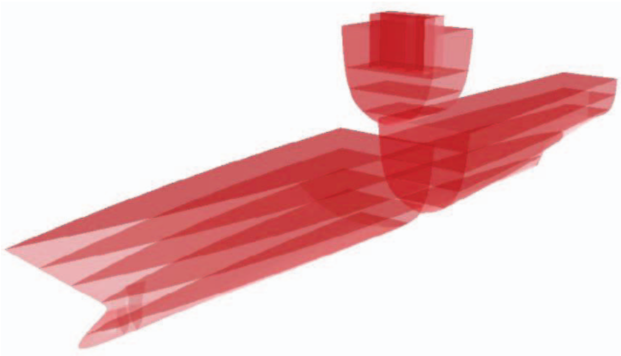

Figure 14. Illustration of Internal Decks & Silo Section

The hull is iteratively altered to meet the required parameters, Table XIV below shows a comparison of Co-efficient values calculated during the parametric survey and those obtained through creation of model in PARAMRAINE®.

TABLE XIV. FORM PARAMETERS V1 & V2

	Required	V1 Achieved	V2 Achieved
Cp	0.62	0.63	0.64
Cb	0.47	0.473	0.46
Cm	0.758	0.76	0.72

B. LCB Sensitivity

A study was undertaken to understand the effect of changing LCB on the overall resistance of the hull form. It is considered pertinent as the location of the silo could be seen to force the LCB forward away from its normal position. The actual LCB position of V1 calculated through PARAMARINE® and the ratio of LCB to Length comes out to be 0.007. To check the effect of moving the LCB a quick resistance analysis is carried out using the resistance spreadsheet [6]. The spreadsheet uses a simple Holtrop and Mennon analysis but is deemed sufficiently indicative at this stage in the design. LCB is varied over the length between a range of -0.05 and +0.05 for both cruise and sprint speed. The results are minimal differences in hull resistance; at sprint speed a difference of 0.2kN in favour of the positive value is seen, compared with a minimal 0.01kN negative change at cruise speed.

Hence, it is concluded that the effect of positioning of silo on hull resistance in terms of movement of LCB is minimal and the bigger driver on position is overall layout and the consideration of 'fair' lines along the hull.

C. Final Model

Representations of V1 and V2 variants are seen below in "Fig. 15" with complete zoning for all machinery rooms (Green) the mission bay (Orange) and tanks (Pink). The silo section is seen just aft of the first superstructure island, concealed by RCS screens to make the two islands appear singular and reduce radar cross section.

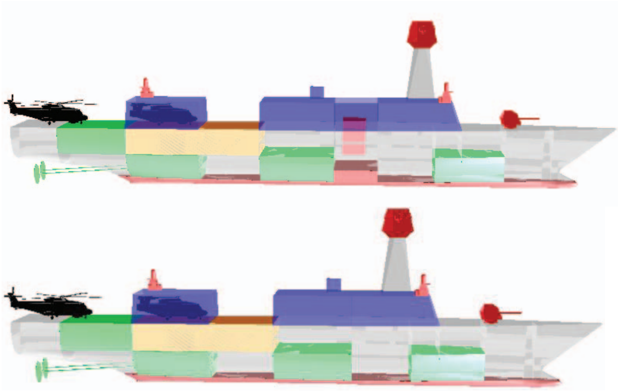

Figure 15. PARAMARINE® model of both variants

XI. GENERAL ARRANGEMENT & LAYOUT

A. Design Considerations

Before a detailed layout can be worked up it is first necessary to consider the over ruling constraints acting on the design.

The main capability of the design lies in the large integral mission bay and its access routes; sufficient volume must be assigned so as to fit the required equipment, its supporting infrastructure and space for launch and recovery of men and material. This naturally leads to its placement at stern of the vessel where it must compete for space with towed array equipment and steering gear. Moreover, Access must also be allowed to the hangar from the mission bay in order to facilitate the operation of Unmanned Aerial Vehicles (UAVs).

The silo section, designed to be removed for the V2 variant is restricted in its position due to its requirement for a parallel section of hull, meaning it is to be placed near amidships of the design. This raises design challenges in maintaining access between fore and aft sections and particularly in superstructure design as the launch cone must also be catered for.

Internal bulkheads are positioned throughout the design to support superstructure blocks ends, load points such as the aft cut up and to meet NES 109 [3] damage requirements. They also require attention wrt general arrangement vs structural strength requirements.

B. *Upperdeck and Combat System Layout*

For V1 variant of primary concern is the location of main integrated mast supporting the MFRAPAR as it must be sufficiently longitudinally from silo so as to ensure clearance from the launch cone of the missiles. However, for both variants (V1 & V2) it is restricted in its forward position by the requirement for low vertical accelerations as a result of pitch.

Superstructure is a major factor in the RCS of a warship and in order to reduce this on the highly survivable TVNS the superstructure is kept to full width and angled. The angle at which the superstructure bulkheads are it is only indicative as shown in "Fig. 16" below.

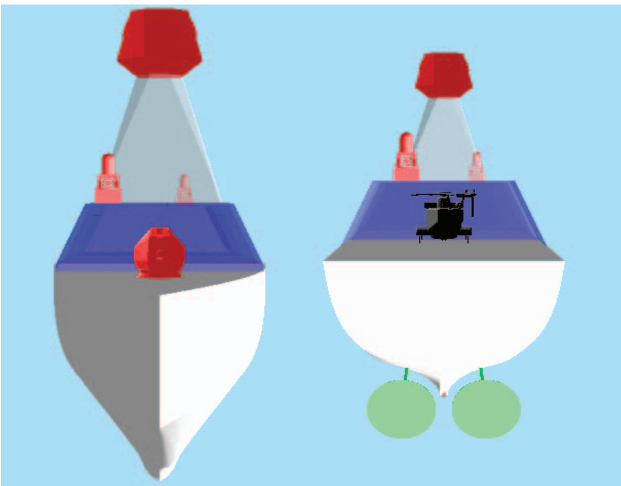

Figure 16. Indicative angled superstructure for reduced RCS

A large flight deck is to be accommodated to allow Merlin EH101 and UAV operations and the possibility of Chinook landings in exceptional circumstances. Upper deck access will be provided through the hangar and superstructure due to restrictions in place from full width superstructure blocks. The Silo block protrudes one metre above the weather deck to allow it to sit on 2 deck without penetration. CIWS in the form of PHALANX units are positioned forward on the starboard side and aft on the port side to give best possible all around coverage from incoming attack. 40mm guns are placed on the large bridge wings on either side and on the flight deck, again to provide maximum coverage. The 155mm gun is placed on fox'l deck as best possible situation and is structurally supported by a bulkhead.

C. *RAS Point*

Replenishment at Sea (RAS) is a lifeline to every military ship while operating at sea for extended durations and long transits. RAS points are located on either side of the aft superstructure behind the funnel. It is positioned close to the aft main access and stores compartment so RAS gear can be quickly obtained and any embarked provisions can be conveniently transported into the ship through the main access point where the ship's crane can lower it down.

D. *Mission Bay Layout*

The mission bay forms a key capability of both variants, which can flexibly reconfigured. The three main options are; Mine countermeasure, EMF or Disaster relief. The location of mission bay is the key driver of the TVNS design; as it provides a huge capability and occupies a large space at the same time.

Considerable consideration has been given to the method of launch and recovery of UXVs from the ship with the two main options being directly from the mission bay itself using side/ stern ramp or from the weatherdeck in a more conventional manner. Launching from the mission bay offers advantages in the handling of UXVs and in that they are launched from a lower height into the water. However such a system would require large heavy and expensive watertight doors with relatively low freeboard and restricts the ship space due requirement of longitudinal partitioning.

For these reasons a more conventional system is chosen whereby equipment is loaded via an access hatch into the forward section of the mission bay either by its own davit/ cranes or with shore side facilities. The decision has been made to limit the number of launch points around the vessel to two (to minimise RCS) and so ships boats are stored in situ at the cranes. To launch a UXV one of the ships boat is brought down into the mission bay for storage whilst the other remains on station. TEUs and heavier equipment are moved around the mission bay by an embarked forklift with smaller equipment being kept on trailers for ease of movement.

The possibility of a lift from the mission bay to weatherdeck was considered, however due potential reliability issues and expense and weight of such a system it was not considered for this particular application. A sketch of this layout is seen below in "Fig. 17":

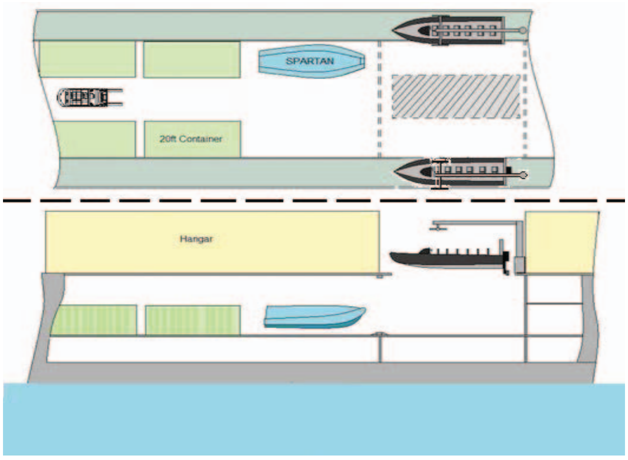

Figure 17. Mission Bay Concept

E. *Machinery Space Layout*

To maintain high survivability machinery spaces were separated longitudinaly and transversely as far as practical. This has been achieved with the concept of IFEP [10] and can therefore maintain the capability of providing power to the ship should one prime mover be compromised. The IFEP has been designed for a 3+1 configuration of diesels + gas turbines respectively. The aft auxiliary machinery room (AAMR) is situated above the damage control deck with the aft engine room (AER) and forward auxiliary machinery room (FAMR) longitudinally separated by 4 compartments with the gas turbine situated between the two.

Moreover, the two Advanced Induction Motors (AIM) are separated by both longitudinal and transverse bulkheads.

F. *Accommodation Layout*

The accommodation layout is designed for the wartime scenario whereby the complement onboard the ship is at its largest with 218 people onboard. Being a modern frigate the accommodation standards with regards to space are exceeded. A twin port-starboard passageway layout is selected for the ship allowing for easy access. This layout also increases the survivability of the ship, by providing extra escape and access routes.

116 Junior rates can be accommodated on deck 3, with ample accommodated for a training margin, located in 6 and 8 Berths cabins. On Deck 2 immediately above the Junior Rates, the CPOs and the POs are located. The layout is very similar to the Junior Rates accommodation. However, CPOs are located in 2 berth cabins and POs in 4 berth cabins. The accommodation layout for 2 Deck can be seen in "Fig. 18".

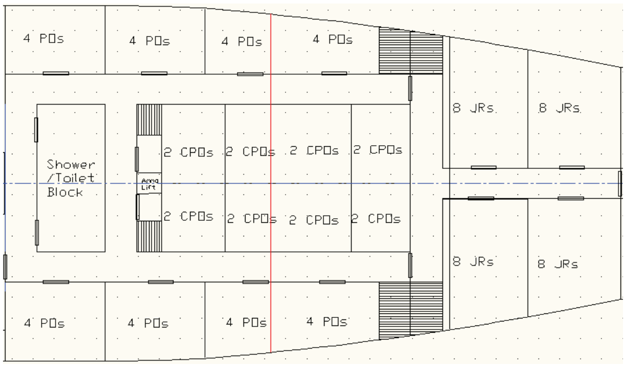

Figure 18. 2 Deck accommodation layout CPO/ PO

The officers accommodation is located in the forward superstructure on the weather deck with the majority of officers having large single berth cabins. The Officers are located in close proximity to the wardroom but have easy access to the bridge as well. The CO's has a larger cabin located forward of the officer cabins and has an easy access to the bridge, with stairs located either side of his cabin.

To achieve maximum capability a total of 45 Embarked Military Forces (EMF) will be carried onboard. The mission bay has cabins on either side, allowing the EMF greater comfort than usually provided during temporary detachments on board.

G. *Zoning*

The ship is divided into 4 damage control zones each of which has the capable of running independently. The zones are such designed to increase the survivability of the ship and keep any damage limited within that zone. The zoning concept can be seen in "Fig. 19"

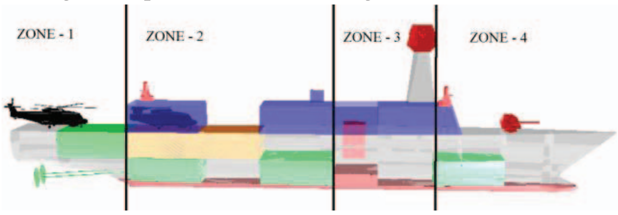

Figure 19. V1 general Arrangement & Damage Control Zones

XII. SURVIVABILITY

The TVNS is to operate in a high threat littoral environment and is therefore required to be highly survivable. Survivability is considered at every stage of the design process and a study into the ship vulnerability is undertaken separately in order to find the survivability of layout.

In order to assess the survivability QinetiQ's SURVIVE ® software is utilised. SURVIVE analyses the chance of a system being knocked out by a single missile and is a useful tool to gauge the extent to which the survivability is achieved. The philosophy towards vulnerability after taking a hit is Float, Move, Fight; and analysis is carried out accordingly.

In the event of a missile strike the primary concern is the ability to stay afloat and is analysed in detail later in the damage stability section. Secondary to floating is the ability to move such that the high value unit can withdraw from combat and survive to fight another day. In Survive the Propulsion system is modelled such that either of the propulsor could retain some sort of power after taking a hit. Using an IFEP layout it is expected that the propulsion system would be highly survivable.

A. *Attack Scenario*

Ship model with all equipment located in their position as per the general arrangement layout, is analysed. The software simulates 300 missile strikes of an Exocet missile (each with a 160kg charge); "Fig. 20" shows a snapshot. For each missile the fragmentation is modelled and any compartment which has a breach is deemed to have all equipment in it destroyed. The missiles are fired in transverse to the ship, which is the worst case scenario when maximum compartments are compromised by the strike.

After the analysis is run, the output is in the form of a statistics file and a pictorial view showing the ship's vulnerability to the system being analysed.

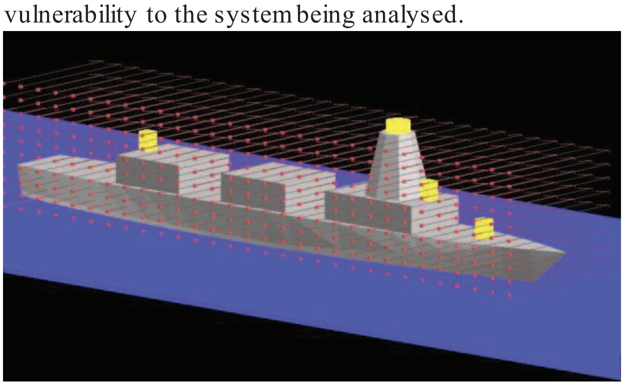

Figure 20. Exocet Missile Attack Scenario

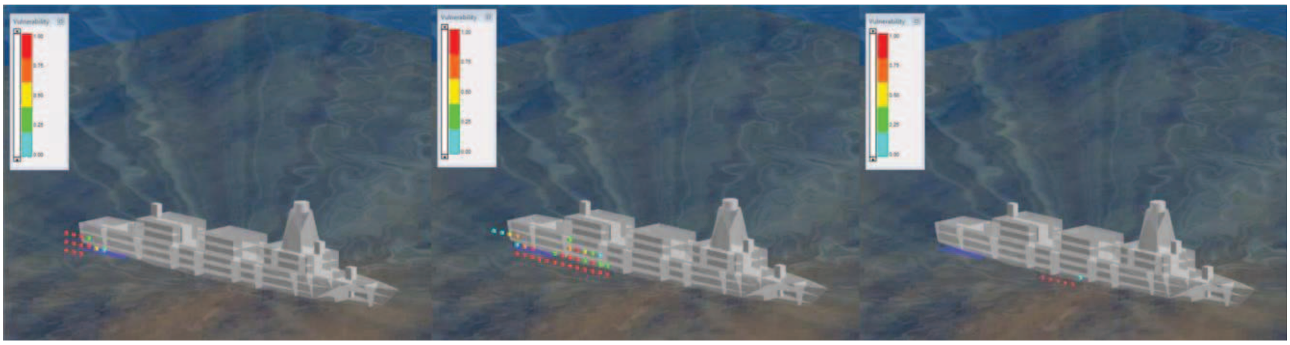

Figure 21. Manoeuvring, Propulsion & Point Defence System vulnerability (respectively)

B. *Survival Analysis*

Of the 300 missiles aimed at the ship, 34 missiles and their fragments hit some form of propulsive equipment. Due to the IFEP 3+1 configuration, the propulsion system proves to be very survivable to attacks on the prime movers, showing advantage of significant redundancy. However, the missile strikes on the waterline in the aft end of the ship, where the shafts run through, caused loss of propulsive power. The results are shown in "Fig. 21" and tabulated in Table XV:

TABLE XV. PROPULSION SYSTEM VULNERABILITY

System	Hits	Survivability
Propulsion	34 / 300	84.6%

To complete the "move" section of the survivability philosophy applied, the manoeuvring system analysis showed that fewer hits affected the rudders as could be expected due their location, hence the survivability of the system when the ship is hit by a missile is greater. The results are shown in Table XVI and visible in "Fig. 21":

TABLE XVI. MANOEUVRING SYSTEM VULNERABILITY

System	Hits	Survivability
Manoeuvring	13 / 300	93.2%

The point defence system is highly survivable due to the excellent redundancy in the layout. The only place that a hit could knock out all point defence capability is a strike at a midships which would damage the switchboards associated to the weapons systems. The results are presented in Table XVII and can be seen in "Fig. 21":

TABLE XVII. POINT DEFENCE VULNERABILITY

System	Hits	Survivability
Point Defence	6 / 300	96.7%

The Survive analysis results above, verify the advantage of having a backup ops room ie a "Cruising Ops room" in addition to the "Warfare Ops room"; proving the result of point defence system survivability to be extremely high. Moreover, the propulsive survivability is also on the higher side, due utilization of IFEP. In order to further enhance survivability which, a drop down pod is placed in the forward section of the ship which can provide a 'limp-home' capability. As a whole this analysis provides better ways of achieving redundancy either by dispersing the systems along the ship or by increase backup systems. Moreover, it can also be used for manoeuvring around ports.

Further work can be undertaken with Survive by running, the simulation with more number and different type of missiles in order to improve the accuracy of the results. Moreover, different dimensions of threats like of mine underwater explosions could be particularly useful for assessing the ships suitability for MCM.

XIII. STABILITY

An initial crude estimate of stability for V1 and V2 is determined during Parametric Survey, which resulted in a stable value of GM. This is helpful in determining limiting values for stability like beam vs superstructure volume with the use of empirical formulae. More accurate stability analysis is performed with the help of PARAMARINE® by placing weights individually as per longitudinal and vertical position of equipment/ machinery and tanks as well. This later provided accuracy in the results of stability, later structural B.M. & S.F, trimming and heeling.

A. *NES-109 Intact*

Stability is considered for three conditions; light, light harbour arriving and deep end of life for both variants. GZ curves for light harbour arriving condition of V1 is shown in "Fig. 22".

Intact stability for ship is found using different NES-109 criteria [3] of "Curve Shape", "Harbour", "Fire Fighting", "Wind Heeling", "Ice Wind", "High Speed Turn", for either of V1 and V2, present in Table XVIII.

TABLE XVIII. STABILITY SUMMARY

Loading Condition	Mean Draught (m)		Displacement (m)		Trim BP (m)		VCG (m)	
	V1	V2	V1	V2	V1	V2	V1	V2
Light Ship	4.71	4.2	3822	3358	1.61	1.29	7.57	7.41
Light Harb Arriv	5.18	4.73	4675	4027	0.82	0.65	6.99	6.85
Deep Ship	5.74	5.66	6185	5298	0.02	0.30	6.70	6.51

Light ship condition being the worst from intact stability point of view marginally passes the criteria of harbour, curve shape & ice wind, but its not a major concern as it is not an operational condition i.e without any fuel, personnel and stores. Moreover, it can be improved through ballasting of tanks. Some of the detail of the light ship criteria limiting and actual values are presented in Table XIX.

TABLE XIX. LIGHT SHIP CONDITION CRITERIA FOR V1 & V2

	Criteria Limit	V1 Values	V2 Values
GMtf (m)	0.3	0.526	0.562
area_0_to_30 (mrad)	0.08	0.067	0.074
area_0_to_40 (mrad)	0.133	0.121	0.136
area_30_to_40 (mrad)	0.048	0.054	0.061
GZmax (m)	0.3	0.662	0.739
GZmax_angle (deg)	30	50	50

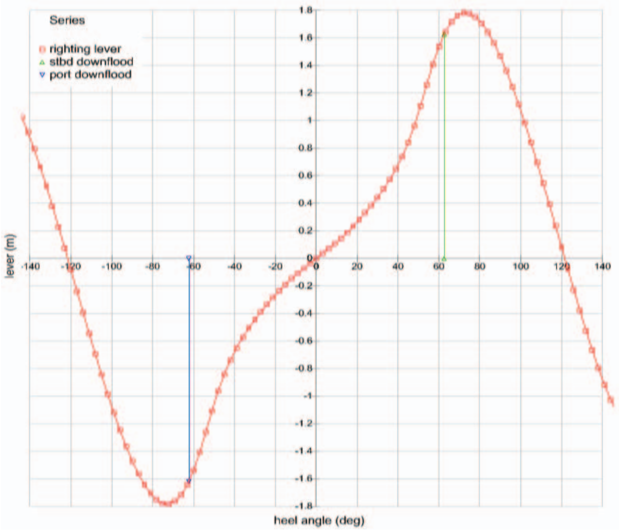

Figure 22. GZ Curve (Light Harb Arriv V1)

Whereas both variants V1 & V2 pass all the criteria of intact stability in light harbour arriving and deep ship condition. The downflooding points are inserted as warning points in PARAMARINE®, to indicate heeling angels at which downflooding occurs for the deck openings. The resulting three main downflooding points are:

a- Gas Turbine Intakes
b- Mission Bay Opening
c- DG Exhaust at stern

To improve GT intakes are shifted from 01 deck to 02 deck; and resultantly the GZ curtailed at 45^o is improved to 57^o. Whereas, the mission bay hatch/opening and DG exhaust are not a concern as downflooding occurs beyond 95^o and 140^o.

Moreover, turning radius results for "High speed turning criteria" [3] which requires the ship to keep the heel angle less than 20^0 are as follow (Table XX):-

TABLE XX. TURNING RADIUS FOR V1 & V2

Loading Condition	V1 Turning Radius at 30 kts. (m)	V2 Turning Radius at 22 kts. (m)
Light Harbour Arrive	448	197
Deep	182	85

B. *NES-109 Damage*

As per criteria a monohull warship greater than 92m, as defined in [3] should be able to take a damage length of 15% of WL or 21m, either of which is greater. In this case 21m translates into 3 or 4 no. of compartments.

The damage stability will revolve around V2 as it is shorter than V1 by 10m, i.e. lesser reserve of buoyancy. All damage cases are conducted for both light harbour returning and deep end of life condition; and deep condition is found to be the worst. For damaged compartments Vertical damage extent upto 1 Deck is assumed.

Initially the concept of bulkheads was defined as after cutup, engine room, structural continuity (i.e. landing of superstructure upon continuous bulkheads) and collision bulkheads. After conducting damaged stability through PARAMARINE® the greatest damage case results produced can be seen in "Fig. 23, 24" where deck immersion is visible as cross cyan coloured lines.:-

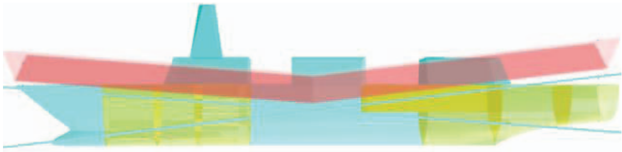

Figure 23. Compt. C,D,E or I,J,K (V1 Deep Damage)

Figure 24. Compt. C,D,E or H,I,J (V2 Deep Damage)

To improve the damaged stability damage control deck is shifted up by 0.8 m, which is compensated by reducing the deck height of Deck 3 and Deck 2 by 0.4m each (3m to 2.6m). This improves the damaged stability, but to a limited extent. Finally a bulkhead is introduced at aft end between bulkheads at 0m and 11m, and intelligent reallocation of bulkhead spacing in the fore part. The improvement in the damage cases can be seen in the following "Fig. 25, 26" as there is no deck immersion:-

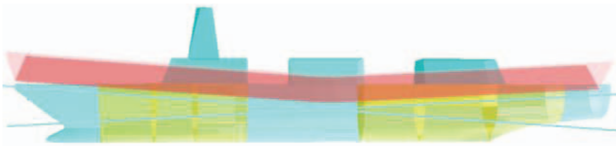

Figure 25. Compt. C,D,E or H,I,J (V1 Deep Damage)

Figure 26. Compt. B,C,D or H,I,J (V2 Deep Damage)

Through re-analysis it is found that the vessel passed all damage criteria. Major damage cases are as summarized in Table XXI below:

TABLE XXI. DAMAGE STABILITY SUMMARY

Damaged Compartments	Trim m	Draught m	Trim m	Draught m
	V1		V2	
BCD			-8.57	7.09
C D E	-9.81	7.95	-10.88	8.16
D E G			-6.562	8.16
E G H			-3.15	8.01
G H I	-2.55	7.44		
H I J	-7.16	7.42	-7.34	7.8

Moreover, additional asymmetric damage is also assessed [3], although it is required for ships with a wide beam i.e catamaran, swath, aircraft carrier; the resulting heel is within range.

C. Red Risk & V-Lines

A dynamic allowance over and above the static damage waterline is included in order to account for heave and roll in a seaway [11]. A depiction of the same can be seen in "Fig. 27".

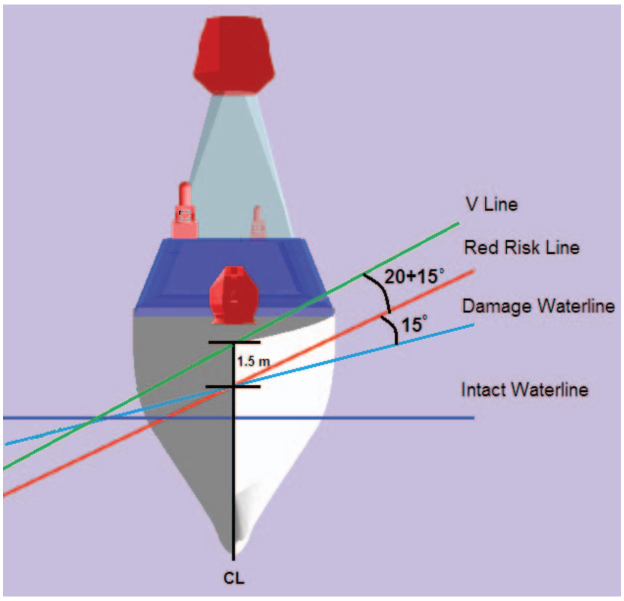

Figure 27. Red Risk & V Lines

Deck 3 was initially assumed as damage control at a height of 8.3m (1.5+3+3.8); a continuous deck. As per [3] the damage control deck should be above the lower most apex of the Red Risk Line. Hence, Red Risk Lines are plotted with the help of PARAMARINE® and every compartment is analysed. The results require improvisation in Damage Control deck either through a discontinuous combination of Deck 2 & 3 or shifting the damage control deck a deck higher to Deck 2. To have advantages of a continuous damage control deck, Deck 2 is chosen.

Then V-lines are redrawn, to determine the required level of watertight integrity. V lines are drawn at a height of 1.5m above Red Risk Lines with an added angle of 20^0 either side. The following "Fig. 28, 29" shows the red risk lines when Deck 2 is set as Damage Control Deck.

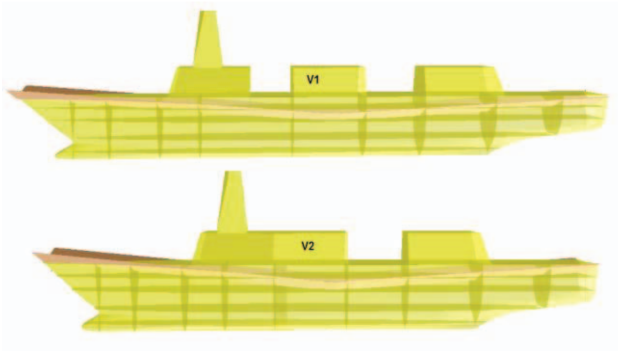

Figure 28. Red Risk Lines

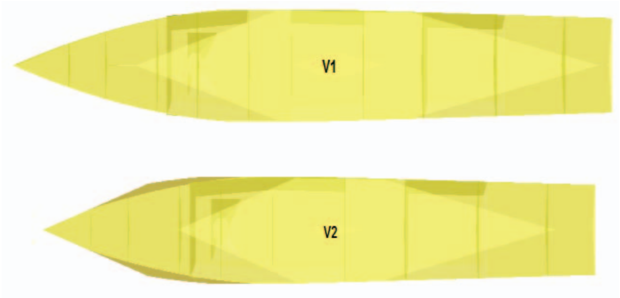

Figure 29. Red Risk Zone (Light colored rhombus area)

After shifting of Damage Control deck form Deck 3 to Deck 2, the through bulkhead openings in Deck 3 will be removed and continuity in the mission bay will be through the side walkways.

XIV. SHIP STRUCTURES

In order to verify initial structural weight estimates and to validate the design, analysis of the most structurally challenging section i.e mission bay near to amidships is undertaken. As a result effective thicknesses are obtained, corresponding to the required sectional modulus, which are then converted to plate thicknesses and stiffener sizes.

The resulting structure is then tested against a series of failure modes and then a final structural weight is estimated from the resulting structure. Moreover, the helicopter flight deck is designed to withstand the crashing loads of a Merlin helicopter.

Standard 'B' quality steel is chosen as the construction material with material properties as presented in Table XXII:

TABLE XXII. MATERIAL PROPERTIES

'B' Quality Steel	
Young's Modulus	207 GN/m^2
Poisson's ratio	0.3
Yield Stress	310 MN/m^2

A. Design Bending Moments and Shear Force

All weights are inserted into PARAMARINE® model and still water moment bending moments and shear forces are calculated. The model is then balanced on an 8m [1,12] wave and results for bending moments and shear forces are obtained. These two sets of results are then used by the program to output a set of design bending moments and shear forces.

This process is carried out for both V1 and V2 variants, V1 bending moments and shear forces are larger of the two variants and this in turn is used for structural design. "Fig. 30" gives the resulting hog and sag distribution along the length of the vessel. Of interest are the sag moments forward of the superstructure, seen to be negative. This area lines up with the forward machinery room as well as the main gun at fox'l, considerable concentrated weights, combining to produce a negative sag or slight localised hogging moment. This is seen more clearly in a plot of shear force along the length of the ship in "Fig. 31".

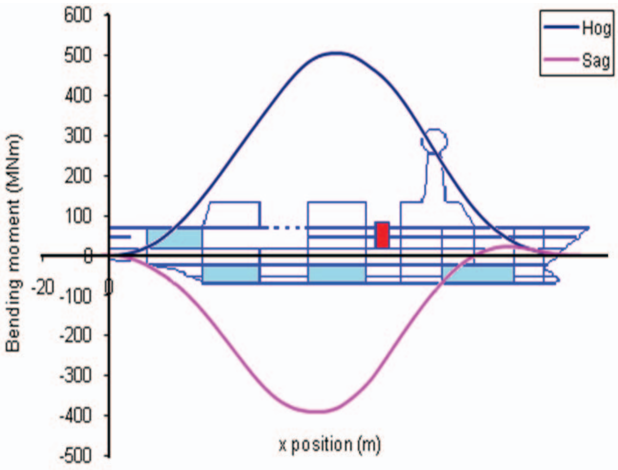

Figure 30. Design Bending Moments – Hogging & Sagging

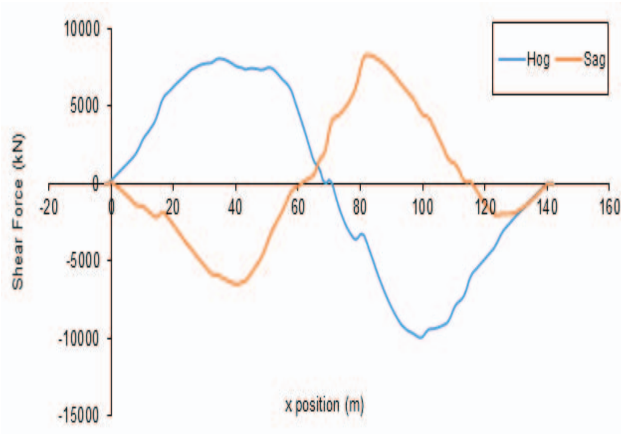

Figure 31. Design Shear Forces – Hogging & Sagging

No slamming correction has been applied to the moments [1,13], as it is not applicable to the section of choice i.e. mission bay near amidships. Worst case loading is applied to the section of choice (mission bay near amidships), and corresponding bending moments and shear force are as follows (Table XXIII):

TABLE XXIII. DESIGN BENDING MOMENTS AND SHEAR FORCE

Design Bending Moment - Hog	504 MNm
Design Bending Moment - Sag	391 MNm
Design Shear Force	9.92 MN

B. *Choice of Section*

Usually structural analysis is carried out at midship section, where bending moments are at their peak. However, in case of the V1/ V2 design this is not the case, as the large mission bay located towards the stern of the vessel with the 12 metre long by 5 metre wide access hole through weather deck proves to be the worst case scenario; from structural point of view. Hence, this location is chosen at a distance of around 40m from the stern. From damage stability point of view, the mission bay has two longitudinal bulkheads running down its length on either side. As these bulkheads do not run the whole length of the ship, an allowance is made for their reduced structural efficiency. Using a method outlined in Chalmers [12] an efficiency based on the section being a distance of 1.5m from the transverse bulkhead is taken as 20% and applied to the area of the section in calculations.

The worst case bending moments and shear forces found above through PARAMARINE® are applied to this section, along with a 10% increase as per [12]. The cross section of the selected structure is depicted below in "Fig. 32". The curved sections are modelled as straight edges for simplicity and numbered for later reference.

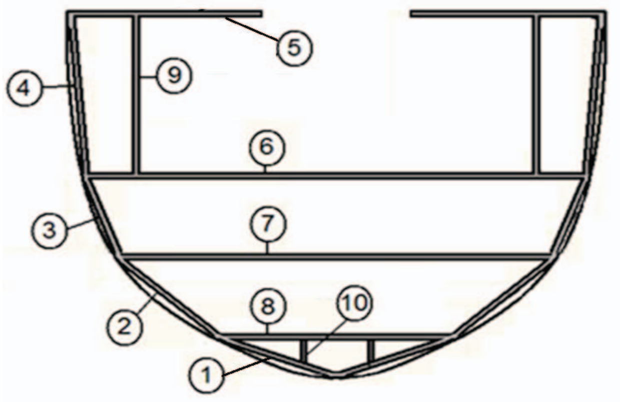

Figure 32. Mission Bay Section

C. *Choice of Effective Thicknesses*

Initial estimates of effective thickness already obtained are used to obtain corresponding second moment of area and neutral axis position, and then related modulus of section at deck and keel. These moduli are then used to calculate the stresses in the deck and keel using design bending moment. And the safety limiting factors for yield are 57% for deck and 43% for keel [12].

Effective thicknesses are then calculated corresponding to the modulus requirements. Table XXIV below gives the details of the chosen thicknesses, cross referenced with numbered section seen in "Fig. 32".

TABLE XXIV. EFFECTIVE THICKNESSES AND PROPERTIES

Sec No	Eff Thick	Width	Depth	Length	I section	y	I Part
	mm	m	m	m	m^4	m	
1	13	8.1	3	8.64	1.48E-06	-4.69	2.47
2	13	6.16	6	8.59	2.34E-01	-3.19	1.14
3	13	2.1	6	6.36	2.34E-01	-0.19	0.00
4	13	0	12	12.00	1.87E+00	5.06	3.99
5	15	12.38	0	12.38	3.48E-06	8.06	12.05
6	15	16.35	0	16.35	4.60E-06	2.06	1.04
7	12	14.26	0	14.26	2.05E-06	-0.94	0.15
8	11	8.1	0	8.10	8.98E-07	-3.94	1.39
9	11	12	0	12.00	1.58E+00	5.06	3.37
10	0.012	0	1.3	1.30	2.20E-03	-4.69	0.34

Material yield stress and design permissible stresses along with calculated stresses expected in the structure as a result of the chosen effective thicknesses are seen below in Table XXV:

TABLE XXV. CRITICAL STRESSES AND DESIGN DETAILS

Yield Stress	Pa	3.10E+08
Stress Limits - Deck	Pa	1.77E+08
Stress Limits - Keel	Pa	1.33E+08
I Section	m^4	29.876
Z Deck	m^3	3.709
Z Keel	m^3	5.487
Sigma Deck - Hog	Pa	1.36E+08
Sigma Deck - Sag	Pa	1.05E+08
Sigma Keel - Hog	Pa	9.18E+07
Sigma Keel - Sag	Pa	7.13E+07

D. *Failure Modes*

After determination of effective thicknesses it is necessary to size the plating, longitudinal stiffeners and their spacing to ensure they are sufficient to pass the following cretira:

a. Compressive Strength
b. Plate Buckling
c. Interframe Buckling
d. In Plane Tripping
e. Lateral Tripping

Spacing is restricted by practical considerations and so can be no less than 400mm to allow ease of fabrication/ welding. Similarly a maximum spacing is calculated so as to ensure that the stiffeners make a suitable contribution to the overall strength of the plating, defined by the plate slenderness ratio beta, being no more than 2.5 [1].

Standard stiffeners as defined in [17] are selected to be used in the construction, which allow for standardization and ease of inventory and fabrication management. Options for selection of plate thicknesses stiffener spacing and stiffener types [17] for weather deck are seen summarised in Table XXVI:

TABLE XXVI. PLATE THICKNESSES & STIFFENER TYPES AND SPACING

Plate Option	Thickness (m)	Spacing	Section
1	0.010	0.49	3
2	0.010	0.49	3
3	0.010	0.49	3
4	0.008	0.402	4
5	0.011	0.489	4
6	0.011	0.489	4
7	0.008	0.45	4
8	0.008	0.45	4
9	0.008	0.45	4
10	0.010	0.421	2

Spreadsheet [13] is used to check the design against all the failure modes. Finally, transverse spacing is taken as a standard 1.4m and transverse stiffeners are sized to be a minimum of two sizes larger than the longitudinal stiffeners that intersect them, meaning Type 6 [17] will be used.

E. *Superstructure*

The superstructure is in 3 sections/ islands and for the simplification of calculations and understanding it is assumed to be non-contributing to the overall strength of the hull girder. However, this is a conservative assumption, as all superstructure sections are full width to keep RCS low, and superstructure would be contributing in structural strength. Plating is assumed to be a minimal thickness with localised reactive armour where required in areas such as the air magazine and ops room.

In a later design iteration it would be advantageous to research the possibility of composites in the construction as great reductions in weight could be achieved. Bulkheads are placed to ensure that all superstructure islands begin and end on a support; these supporting bulkheads are designed to extend at least 2 decks below the superstructure they are supporting.

F. *Fatigue*

A Brief Fatigue analysis is carried out using the methodology laid out in [15]. Analysis is carried out for the worst case weld class as well as the preferred B quality weld [18]. A minimum sectional modulus is generated from the analysis which the design moduli should exceed. The calculation is carried out based on a lifetime wave encounter of 10^8 [14].

With worst case weld classes the minimum modulus is seen to be 1.5 and with B quality welds a minimum modulus 0.8. Thus achieved modulus exceeds those required by this fatigue analysis, and hence structure is considered adequate to with stand fatigue.

G. *Structural Weight Estimate*

The tool [15] is used to provide an estimate of structural weight to be compared to that assumed in initial sizing. Scantlings from the initial sizing are fed into the spreadsheet along with ship characteristics, design bending moments and details of additional decks. The resulting structural weights for V1 and V2 are 1920te and 1780te respectively. These compare favourably with the initial sizing values of 1722te and 1565te respectively, with an increase of 11%.

H. *Helicopter Deck Sizing*

The helicopter deck is an area of particular loading under the condition of a helicopter crash where it must be able to withstand three times the mass of the helicopter being used landing on an area equivalent to one tyre [12]. Permissible permanent set is b/50, where b is the stiffener spacing.. After multiple iterations a suitable grillage is finalized as:

i. Stiffener Spacing = 400 mm
ii. Plate Thickness = 10 mm
iii. Stiffener Type = 2 [17]

XV. SEAKEEPING

Ship seakeeping characteristics have significant effects on its operational capability in terms of platform's ability to perform operations and its crew performance (due ship motions affect). Excessive motions may hinder the capability of the platform to carry out its role. This is particularly pertinent in the case of TVNS whereby the launching and recovery of UXV's is essential to the capability of the platform. Therefore, considerations are made throughout the design, such as Circular M [1] being as high as possible to reduce the pitch and heave motions and relatively higher flare in bow section to reduce the slamming loads.

A. *Limitations*

Seakeeping characteristics are assessed using PARAMARINE®, which is limited as it considers all motions to be linear. Therefore, the accuracy of results is limited to pitch and heave motions only; and any heading relative to the wave direction which evokes any form of lateral movement such as sway, roll and yaw results in inaccurate plots. Hence, the analysis carried out is limited to the pitch and heave RAOs (response amplitude operators) and vertical accelerations in head and following seas.

Moreover, in order not to skew the results appendages impacting the Seakeeping characteristics are simplistically modelled; such as a simple twin rudder configuration with no stabilisers alongwith default values for the rudder gain and coefficients and radii of gyration from PARAMARINE®.

Seakeeping is typically carried out by model testing in a towing tank and would yield much better results than the linear analysis used in PARAMARINE®. However, PARAMARINE® can provide a broad overview of the seakeeping characteristics of the hull's performance in head and following seas.

B. *Response Amplitude Operators*

Due to the limitations highlighted above, the RAOs for heave and pitch in head seas and following seas are of the foremost interest. The speeds considered for seakeeping analysis are the cruise speed, 14 knots for both variants, max speed, 28 knots for V1 and 24 knots for V2, and stationary condition. Seastates are used from the Pierson-Moskowitz sea spectrum which is suitable for fully developed seas.

The RAO's with the greatest response for heave and pitch are in following seas, when the ship tends to follow the waves, hence a greater chance of resonance. These can be seen in "Fig. 33, 34".

The respective RAO's for heave and pitch in a Seastate 5 are relatively benign and are not of great concern with regards to resonance. The greatest peak observed for heave is at a frequency of 0.92Hz where the RAO reaches a modest 1.14.

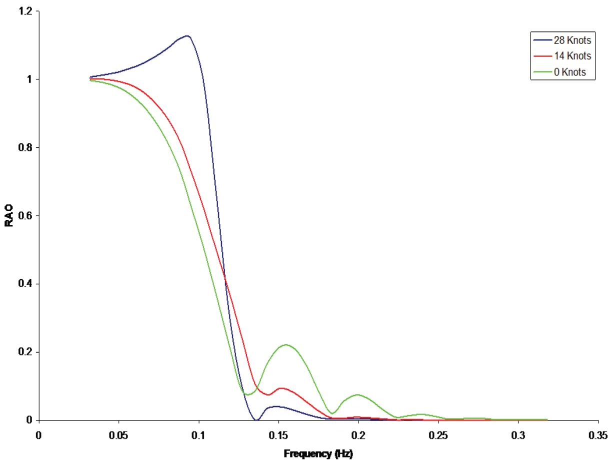

Figure 33. RAO in Heave for Following Seas - V1

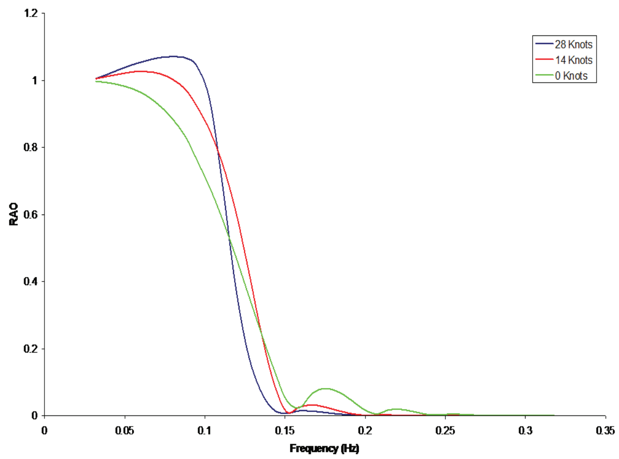

Figure 34. RAO in Pitch for Following Seas - V1

C. *Flight Deck Operations*

Due to the position of the flight deck i.e after end of the ship, it will be subject to larger motions and hence recovery operations for UAVs will be sensitive to heavy landings. Moreover, it has been found experimentally that recovery operations are limited to when the vertical acceleration of the flight deck is 0.2m/s^2. However, helicopters are capable of withstanding larger vertical accelerations and the limiting factor becomes the safe limit that the pilot can land the aircraft, which are limited to the pitch and roll angle of 1.5^o and 2.5^o respectively [1]

UAVs

The vertical acceleration analyzed through PARAMARINE® in different Seastates for head seas at 4 knots is tabulated in Table XXVII. This shows that the limiting Seastate for the UAV operations is top end Seastate 3 which corresponds to a significant wave height of 2.5m with a average period of 5.5seconds.

TABLE XXVII. VERTICAL ACCELERATIONS FOR UAV OPERATIONS

Seastate	Vertical Acceleration (m/s^2)
3	0.06
4	0.22
5	0.4

Helicopter Operations

The pitch angle is analyzed through PARAMARINE® in different Seastates and results are tabulated in Table XXVIII. However, as per earlier mentioned limitations of PARAMARINE® roll angles are not analysed.

TABLE XXVIII. PITCH ANGLE FOR HELICOPTER OPERATIONS

Seastate	Pitch Angle (^{0})
3	0.04
4	0.27
5	0.8
6	1.4
7	2.3
8	4

As per pitch angle results Seastate 6 is the limit for helicopter operations, however it is considered that practically the rolling angles will most likely be the limiting factor.

D. *Motion Sickness*

In order to assess the comfort of the vessel, a MSI (motion sickness indicator) can be used. Ship subjected to high MSI's will greatly reduce the performance of the crew and hence reduced platform capability. There are also limits based on the vertical accelerations which are felt by the crew and systems. The guidance limit for a warship bridge is 1.96 m/s^2 [1].

The best place to analyse the motions are on the bridge as it is high up and therefore likely to be the worst case condition where people are working for long periods. As stated previously, the roll is likely to be a large feature of the MSI, but in head or following seas the vertical motions can be assessed through PARAMARINE®. The MSI and vertical accelerations going at cruise speed for V1 can be seen in Table XXIX:

TABLE XXIX. MSI FOR VARYING SEA STATES ON BRIDGE DECK

Seastate	MSI (%)	Vertical Acceleration (m/s^2)
5	6	1.11
6	15	1.45
7	23	1.796
8	29	2.1

Whilst there are no limits on a warship for MSI, the comfort of the crew is important and the analysis shows that the vertical accelerations become a problem at a Seastate of 8 which is to be expected. A generally accepted value for when motion sickness becomes a problem is when the MSI over a 4 hour period is 25%. The results from PARAMARINE® show that for a 4 hour transit in head seas a Seastate of 8 becomes troublesome. It is unlikely that the ship will be travelling at cruise speed for this long in such a high Seastate and the captain would more than likely reduce/increase the speed to limit the effects.

Therefore, as previously stated the results obtained have limited significance due limitations of PARAMRINE® itself. Notwithstanding the above mentioned values of roll and pitch will be significantly limited through use of stabilizers; whose movements cannot be effectively integrated into PARAMARINE®.

XVI. MANOEUVRING

A. *Directional Stability*

Warships are required to be highly manoeuvrable and are therefore kept marginally directional stable; so that the ship is highly manoeuvrable but still can maintain course with use of directional corrections through rudders. Due lack of information on the effect of interaction between hull and appendages; straight line stability analysis is carried out on the bare hull. Using bare hull derivatives the stability index of the ship is calculated and the stability assessed through following equation:

$$N'_v(m' - Y'_r) + Y'_v N'_r \geq 0 \quad (9)$$

i. N'_v = Non-dimensional derivative of yaw motion due to sway velocity
ii. N'_r = Non-dimensional derivative of yaw motion due to yaw rate
iii. Y'_v = Non-dimensional derivative of sway force due to sway velocity
iv. Y'_r = Non-dimensional derivative of sway force due to yaw rate
v. m' = Non-dimensional mass of the vessel

A ship is directionally stable if this stability index is greater than zero and if the ship has a stability index less than zero it will be unable to maintain a course without constant rudder alterations however it will be highly manoeuvrable. These hull derivatives are usually found through model testing, and in the absence of any model testing, derivatives can be assumed from empirical data. These empirical formulae found in [16] are as follow:

$$N_v = -\rho T^2 L\left(1 - \frac{0.27\tau}{T}q\right). \quad (10)$$

$$N_r = -\rho(0.54L^2T^2 - 2LT^3)\left(1 + \frac{0.3\tau}{T}\right). \quad (11)$$

$$Y_v = -\rho\left(\frac{\pi}{2}T^2 + 0.7BTC_B\right)\left(1 + \frac{2\tau}{3T}\right). \quad (12)$$

$$Y_r = \frac{\pi}{4}\rho L T^2\left(1 + \frac{0.8\tau}{T}\right). \quad (13)$$

$$q = \frac{\pi}{2} + \frac{0.7B}{T}C_B. \quad (14)$$

These are then converted into non-dimensional derivatives and stability index are calculated for a number of speeds, to confirm ship stability at various speeds. Stability index plot for both variant is shown in "Fig. 35":

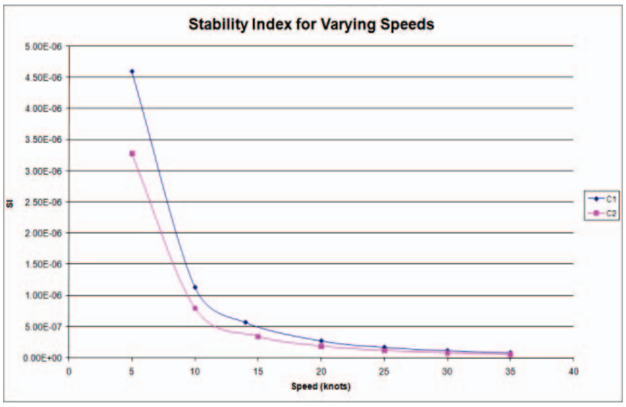

Figure 35. Stability Index for V1 & V2

The stability index plot for varying speeds shows that the stability index reduces as the speed of the ship is increased. Whilst this is only an indication of the straight line stability however it is reassuring that the ship is able to maintain straight line stability at all speeds and yet highly manoeuvrability. The stability index would be effected by the appendages such as the skeg which have not been taken into consideration in this analysis. It is therefore, recommended that model testing be used in order to achieve more accurate results.

B. *Turning Circle*

Using the stability index a preliminary estimation of the turning circle can be calculated to check if the derivatives produced are in the right region. The stability index at cruise speed for V1 is 3.42×10^{-7}. The turning circle is calculated using a 35^0 max rudder deflection from following equation [16]:

$$\frac{R}{L} = -\frac{1}{\delta_R}\left(\frac{SI}{Y'_v N'_\delta - N'_v Y'_\delta}\right). \quad (15)$$

Where;

$$N'_\delta = a'_r\left(\frac{dC_L}{d\alpha}\right)_R. \quad (16)$$

And

$$Y'_{\delta} = -\left(\frac{dC_L}{d\alpha}\right)_R . \quad (17)$$

The turning circle is found to be 510 m. A typical manoeuvrable warship has the ability to turning within 4 times its ships length, and this turning circle corresponds to 3.6 times the ships length and is hence satisfactory.

XVII. COSTS

A. UPC

The Unit Procurement Cost (UPC) is calculated using data from the SDE Data Book [2], manufacturers and previous UCL design exercise logbooks. In the event, that the price is not current, the price is adjusted to account for inflation. The UPC for V1 and V2 is calculated to be approximately £420M and £283M, as show in “Fig. 36” & “Fig. 37” respectively:

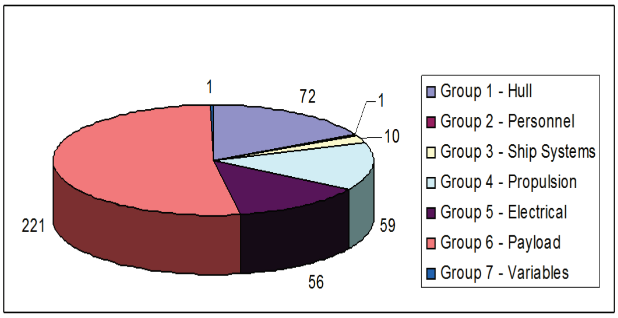

Figure 36. UPC for V1 Variant in £ M

V2 has modest combat systems, less power requirement, lower maximum speed, no VLS silo in the mid-section and lesser length of the ship compared to V1. This corresponds to comparative cost saving of £137M; in Group 1 (hull), 4 (propulsion) and 6 (payload) with a cost difference of £6.5M, £19.1M and £111.6M respectively.

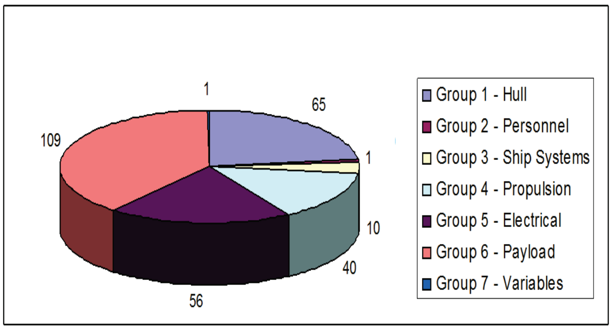

Figure 37. UPC for V2 Variant

B. TLC

The Through Life Cost (TLC) is calculated through the same sources as of UPC. The methodology to calculate the TLC is adopted from the SDE Ship Design Procedure Book [1]. In the event, that the prices are not current, the price is adjusted to account for inflation. The TLC for V1 and V2 is calculated to be approximately £8.5M and £6.5M annually; presented in “Fig. 38” and “Fig. 39” respectively:

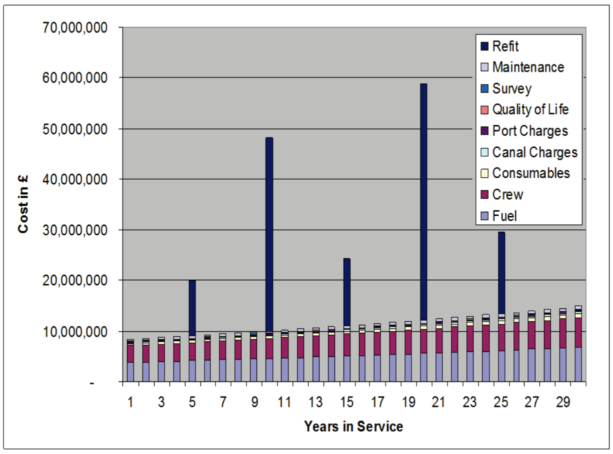

Figure 38. TLC for V1 Variant

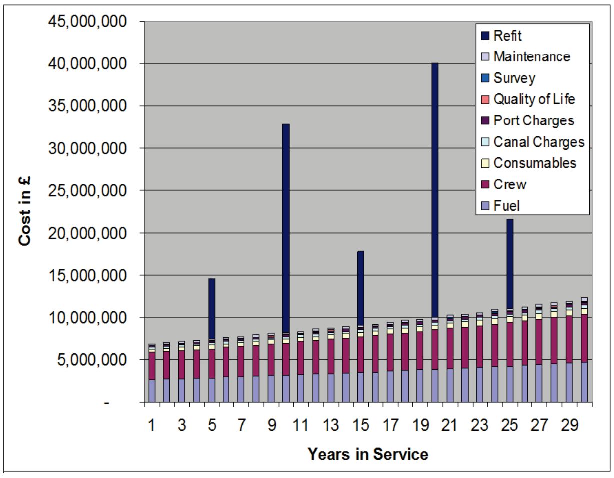

Figure 39. TLC for V2 Variant

C. Economy of Scale

In production of ships, the production cost will reduce as the production number increases. The economy of scale of producing the number of ships can be estimated by using the formula below [2] and represented in “Fig. 40”:

$$UPC_{ship,n} = UPC_{ship\,no.\,4} \times 1.16 \times ship_n^{-0.105} . \quad (18)$$

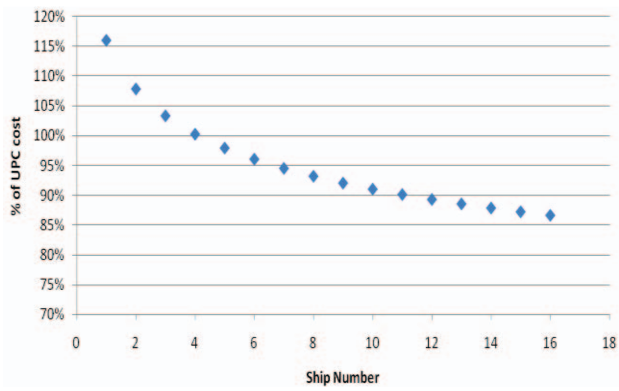

Figure 40. UPC 7.5% Learning curve [2]

Table XXX shows the UPC of V1 and V2 for series production with a reduction in cost resulting from learning curve [1]:

TABLE XXX. UPC FOR VARYING PRODUCTION NUMBERS

Ship Quantity	V1 UPC £M	V2 UPC £M
4	420	283
6	403	271
8	391	263
12	375	252
16	364	245
20	355	239

Based on a combination of constructing 6 V1 and 6 V2, it will provide a significant production cost saving of £45M and £22M for V1 and V2 respectively.

XVIII. CONCLUSION

Both Variants V1 and V2 have been designed with a common hull concept to share as much of the design and production costs to reduce UPC and TLC. This has been achieved through design and systems commonality, resultantly providing flexibility in the platforms. However, all this is achieved at the expense of optimality in both variants.

Payloads have been optimised to produce maximum value for money in terms of capability, and a 10m "pull out section" allows V1 to retain a long range land attack and AAW capability. This additional section also adds extra fuel capacity and an additional operations room to V1. Moreover, both variants utilize IFEP system, which is a cost-effective, flexible and survivable propulsion system. As V2 requires lesser propulsion power than V1, hence it can be flexibly configured and will reduce the UPC of V2; and have a better export market.

The main cost difference between the two variants is reduced payload, less expensive propulsion and relatively reduced hull section for V2. This represents excellent value for money for the capability and flexibility delivered by both variants. Hence, if 6 V1 and 6 V2 are to be produced, it will provide a significant saving of £45M and £22M respectively.

Single sheets characteristic of both variants is presented in Table XXXI below:

TABLE XXXI. SINGLE SHEET CHARACTERISTICS

	V1	V2
Displacement	6048 te	5235 te
Length (overall)	140 m	130 m
Beam (waterline)	16.5 m	16.5 m
Depth	13.5 m	13.5 m
Draught	5.74 m	5.66 m
Speed (Max/ cruise)	29.5/ 15 kts	22/ 15 kts
Endurance (crusie)	10350	8500
Complement (war)	117	114
Cost	£420 M	£283 M

XIX. FUTURE WORK

Following area require further exploration and research:

i. Shear buckling in side plating, torsional issues due mission bay access hatch, structural fatigue analysis.

ii. Finite Element Model (FEM) analysis to examine effects such as whipping and overall buckling and stress concentrations.

iii. Superstructure side plating angles to effectively reduce RCS and resulting structural limitations.

iv. Simulation using SURVIVE ® with and all possible scenarios and threat dimensions (torpedoes, mines etc).

v. Detailed manoeuvring analysis, possibly through model testing at later stages.

vi. Seakeeping analysis with appendages included alongwith their gain and coefficients and radii of gyration values.

ACKNOWLEDGMENT

Sincerest thanks to faculty and staff of Naval Architecture Department at University College London, UK, in particular Ian Randles, Rick Goddard, Tan Hian Nam and Charles Golden for their hard work and special thanks to Professor Paul Wrobel for continuous guidance and support.

REFERENCES

[1] Ship Design Procedure. Department of Naval Architecture, University College London, Apr 2010.

[2] Ship Data Book. Department of Naval Architecture, University College London, Apr 2010.

[3] Def Stan 109, Part 1, Issue 4, UK MoD, Feb 2000.

[4] N Friedman, "British Frigates & Destroyers", Seaforth Publishing, 2008.

[5] John Van Griethuysen, RINA 1994, pg 67.

[6] Hoolotrop & Menon – Ship resistance, Ship Design Exercise tool, Department of Naval Architecture, University College London.

[7] Lewis C, "The Advanced Induction Motor", Power Engineering Society Summer Meeting, Vol.1, July 2002.

[8] Kalsi, S S, HTS Ship Propulsion Motors IEEE, Power Engineering Society General Meeting 2047-2048 Vol.2, 2004.

[9] Mukund R. Pate, "Shipboard Propulsion, Power Electronics, and Ocean Energy", CRC Press, 2012.

[10] I Khan, *IFEP for Nuclear Submarines,* Lambert Academic Publishing, 2012.

[11] Andrew Peters, Rick Goddard and Nick Dawson, "New Approach to the Derivation of V-Line Criteria for a Range of Naval Vessels", The 14th International Ship Stability Workshop (ISSW), October 2014.

[12] D W Chalmer, "Design of Ship Structures", MOD, 1993.

[13] Ship structures failure modes tool, Ship Design Exercise tool, Department of Naval Architecture, University College London.

[14] Surface Ship Structures Notes, Ship Design Exercise tool, Department of Naval Architecture, University College London.

[15] Ship Structural Weight, Ship Design Exercise tool, Department of Naval Architecture, University College London.

[16] Wilson PA & Lewis GDW, "Predicting Ship Manoeuvring Characteristics for Preliminary Design", CADMO 86, International conference University of Southampton.

[17] Stiffeners Data Book, Department of Naval Architecture, University College London, Issue 4, Sep 2002.

[18] Surface Ship Structures Data Sheets, Department of Naval Architecture, University College London, Issue 6, Aug 2001.

[19] R Skarda, & M Walker, "Merits of the Monohull and Trimaran against the requirement for Future Surface Combatant, Design and operation of Trimaran Ships", RINA, 2004.

[20] David J Bricknell & Chris Carlisle, "Propulsion for Fast littoral combatants", RINA Warship, 2004.

[21] I Khan , S Harrison, D Patten and A Raza, "Low Cost Hybrid Propulsion Submarine Concept Design" proceedings of 12th IBCAST, Underwater Technologies, 2012.