THE MULTI ROLE COMBATANT – JACK OF ALL TRADES MASTER OF NONE?

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SUMMARY

For naval vessels Modularity is essentially a design style choice adopted to achieve both aspects of multi-role capability, namely, Flexibility (in deployment) and Adaptability (through life). This paper largely focuses on the second of these, which has been seen to be an attractive objective in Western naval vessel acquisition since the end of the Cold War. A paper to one of this series of warship conferences produced by the author a decade after the collapse of the Warsaw Pact was entitled "Adaptability – the Key to Modern Warship Design". It particularly drew on the difficulties the author had experienced in establishing the case for the Future Surface Combatant (the precursor of the Type 26 Frigate), where the primary capability of this first post-Cold War combatant as a globally deployable class of warship was to demonstrate that Adaptability would be good value for money in an uncertain geopolitical environment.

The paper commences by revisiting the case for Adaptability nearly two decades on from that first consideration and whether the same drivers for Adaptability and advances in Modularity have made the case for multi-role combatants more convincing or whether they are still prone, if they are not truly "First Rate" designs, to be "Jacks of all trades, yet Masters of none?" Next the paper reviews past warship designs that have been inherently adaptable, leading on to consideration of "margins", the traditional way naval ship designers have been able to incorporate a measure of adaptability. However, non-ship design aware procurement authorities, have continued to squeeze seemingly generous margins as a short sighted means of achieving "savings" in the procurement element of defence budgets. There are of course other features, necessary to achieve Adaptability. Thus the paper explores how an adequate consideration of the ship architecture might provide an adaptable design and, specifically, how adopting Modularity to achieve this, can be explored early in ship design. Finally, leading on from the exploration of Adaptability, the paper concludes by a considering the Trimaran configuration. This configuration remains a highly attractive overall Style and ship configuration choice for future warships, precisely because it readily provides so many of the features that are seen to be appropriate in an Adaptable Multi-role Warship, which can be configured to avoid the Second-Rate "master of none" trap.

1. INTRODUCTION - ADAPTABILITY THE KEY CAPABILITY FOR MODERN WARSHIP DESIGN

The choice of a modular "Style" (Andrews 2017) for a naval combatant is both a highly significant design choice and also a direct physical solution to achieving a multi-role capability in a (potentially) satisfactory manner. That is to say in the most "cost effective" manner in a defence acquisition environment ever more constrained by budgetary pressures, particularly on warship procurement. The pertinent question, with the loaded term "cost effective' (see Hockberger (1993) for an analysis of the US Navy's adoption of Cost and Operational Effectiveness Assessment practice), is whether this is both effective in fleet and ship performance terms and, hence, value for money (VFM). The latter should be in terms of the naval budget, rather than just applying the usual key measure of individual ship procurement, namely (for UK vessels), Unit Procurement Cost (UPC), which itself is seen as a dubious basis for VFM (Andrews 2018a).

It could be said that Modularity is a Design Style solution to the issue of Adaptability, which has been an objective to the fore of naval ship acquisition since the end of the Cold War. It was thus addressed by the author in a paper presented to the RINA 2001 Warship Conference (Andrews, 2001), when it was seen to be the prime capability sought in new UK naval combatants in the uncertain world emerging after the collapse of the Soviet Union. At that time all existing naval vessels, including those in the shipbuilding programme under way, such as the Type 23 Frigates and the ASTUTE Class SSNs, had been conceived at the height of the Cold War when the prime direct naval threat was the massive submarine force built up by the Soviet Union. So multi-role vessels were not as appropriate and ASW was seen as the over-riding warfare domain, with AAD as a necessary adjunct to protect the main UK maritime forces in that primary ASW role. Thus for example both the Type 23 Frigates, as initially developed from specific operational analysis of intended towed array sonar operations in the GRIUK Gap, and the INVINCIBLE Class carriers, ordered as ASW helicopter carriers, were both only belatedly modified to have more general purpose or multi-role capabilities. So the Type 23 had a medium calibre 4.5 inch gun added very late in the design (post the Falklands Campaign (Thomas & Easton, 1992)) and the carriers incorporated the (multi-role) FRS (Fighter, Reconnaissance and Strike) Sea Harrier (Honnor & Andrews 1982). The latter incorporation commenced in May 1975 two years into the build of the First of Class when it had become obvious that the RAF could not provide the naval air cover it committed to give. That commitment having been the basis of the 1996 decision to scrap the programme to procure the much larger fixed wing capable CVA01 Class carriers.

The 2001 paper on Adaptability identified two prime reasons why, post the Cold War, future naval vessels should have Adaptability as their primary capability driver:

a. The geopolitical environment in which future naval operations would be conducted was likely to be highly unpredictable, in marked contrast to the operational context in which the vast majority, if not the totality, of existing warships had been designed. The US Navy then led on the way forward by refocusing the operational stance of Western navies post-Cold War with the doctrine of "From the Sea" (Kelso, 1992). In the case of the R.N. the political redirection was spelt out in the Strategic Defence Review of 1998 (HMSO, 1998). The SDR therefore emphasises the need for the UK Defence Forces to operate world-wide and across a broad range of Defence Missions. These range from, at the 'hot' end, full power block confrontation (as in the Cold War), through UN and NATO Peace Keeping to Defence Diplomacy and Constabulary tasks (such as countering the illegal drugs trade and piracy). This resulted in requirements for new warships being less amenable to precise Operational Analysis (OA) scenarios, together with an emphasis on " flexibility" in operations and the ability for the basic design to readily accommodate new roles and provide new capabilities in service. This was seen as being achieved through built in flexibility and incorporating adaptable features to more readily accommodate the introduction of previously unforeseen/immature new roles and technologies. Needless to say this is a far more demanding design requirement than the previous approach driven by highly tuned OA based requirements. In part this new stance led to the 1998 SDR strongly emphasising the need for all new major defence acquisitions to be designed for Technology Insertion (HMSO, 1998).

b. The second driver, which did not really change with the end of the Cold War (it just got worse), was the budgetary squeeze on naval acquisition. In major defence procurement, almost from time immemorial, there has usually been a reluctance in a democracy to pay any more than the absolute minimum for a new military product. Until very recently this meant minimising the initial procurement cost ('maximising the bang for the Buck') and very often at the price of increasing the running costs, including the ability to upgrade the new product through out its operational life. This can be seen at an extreme for naval vessels, which as the largest of complex individual military units, have highly politically visible procurement costs. With the end of the Cold War, the victorious democracies looked to the Peace Dividend to reallocate national resources away from defence, and so concurrently with the perceived need for less highly tuned warships was the pressure to reduce the cost of warships, however that is quantified. This has occurred despite the recognition that the through life costs, rather than just initial procurement costs, ought to govern defence equipment acquisition decisions. So alongside the reassessed national defence imperatives, warship designers had to refocus on the challenging issue of "Design for Adaptability".

This design intent is considered to be a significant challenge, at least in the case of warship design, because warships have historically been inherently flexible in their broad design intent and, pre-eminently in the Royal Navy, in their deployment as instruments of national policy. For this reason the next section reviews past warship designs which have been inherently adaptable. This leads on to consideration of "margins", which can be said to be the traditional way naval ship designers have been able to incorporate a measure of adaptability. However, procurement authorities, being largely unaware of the nature of ship design, have continued to squeeze what they consider to be generous margins, as a short sighted means of achieving apparent "savings" in the procurement element of defence budgets. Yet, adequate margins remain necessary if not sufficient to provide adaptability in a warship. In discussing the other features, which are seen to be required to achieve Adaptability, particular attention is focused on the architecture of the adaptable design and how well Modularity, as a means of achieving this, can be explored early in ship design. Finally, leading on from the exploration of Adaptability, the paper concludes with a reassessment of the Trimaran configuration for naval combatants. This configuration is seen to be a highly attractive overall Style option and ship configuration choice for future warships. That is precisely because it readily provides so many of the features that are seen to be appropriate in an Adaptable Multi-role surface combatant, seen as able to avoid the second-rate "master of none" trap.

2. DESIGNS THAT HAVE BEEN INHERENTLY ADAPTABLE

This section looks at some specific warship designs with contrasting approaches to the way in which the need for adaptability has been achieved. The designs are largely of warships which have been in service in recent decades, rather than paper designs, and where often contrasting views have been expressed as to the degree to which they have meet their design intent and often, even, the validity of that intent. They are largely British designs, which have been described in RINA papers, but in addition for those designs reference has been made to Brown's RCNC history (Brown, 1983), which captured individual designers' comments often relevant to design for adaptability. All the designs are of the Destroyer/Frigate category, with one exception (The INVINCBLE Class Carriers), and there is also one non-UK designed example (The SPURANCE/TICONDEROGA Classes) as it is a well documented example of margin erosion over the life span of the basic design. The discussion presented focuses on the issue of adaptability and clearly cannot do justice to the individual designs in the round, nor fully capture the complexities of the many issues, other than adaptability, which may have been seen to have been more significant to their designers in many or indeed most instances.

2.1 FIRST AND SECOND RATE DESIGNS

In an early study into the nature of ship cost, Brown and Andrews (1980) drew attention to a series of R.N. ship designs to point out that certain ship classes, which had been specifically designated 'first rate' or 'second rate' designs, invariably showed that the latter were poor VFM. This applied to the First World War battleships of the Queen Elisabeth Class and the Revenge Class, where the latter 'cheaper' class were far less effective and clearly less VFM shown by the latter's inability to be upgraded over a thirty year life. In WWII the early convoy escorts, the Flower Class corvettes, were also poor VFM in that role compared with the later Castle and Loch class frigates. Immediate Post War first and second class ASW frigates were produced (Types 12 and 14 respectively) and while the former led to the very successful LEANDER Class, the Type 14s were soon disposed of as lacking the flexibility in the Cold War era, after the Korean War. This result occurred despite all of the first rate designs being initially considered 'too expensive' and the second rates seen to be the means of increasing hull numbers for broadly the same primary (ASW) role. All these comparative designs well exhibit the overall design style choice being made from which all the capabilities flow (Andrews 2017).

2.2 COUNTIES COMPARED TO TYPE 42 DESTROYERS

The contrast between the RN's first two classes of missile armed Air Defence Destroyers, namely the County and Type 42 Classes (Purvis, 1974), could not be more marked with regard to Adaptability. Although the Counties originated as large gun destroyers they were quickly redesigned to be the platform for the new large Sea Slug AAW missile system. They became a large comfortable design, which was configured with particular attention to the ship's services, an essential feature if a design is to be adaptable through life. This ability was tested late in the design rather than in service, when the requirement to add a hanger and flight deck space for the not inconsiderable Sea King helicopter was imposed by the Admiralty Board. That this could be done, and incidentally several of the class late in their life could be significantly modified to carry several Sea Kings by the Chilean Navy, demonstrates that a sensibly designed and generously margin provisioned ship can be highly adaptable. The Type 42 Destroyer design was in stark contrast, in that as a clear victim of being 'designed down to a price' (Purvis, 1974) there were no margins for future technology insertion or role flexibility. The very apparent short sightedness of this approach was revealed when the last batch of the class had a mid-body addition on build, to give at least the hydrodynamic capabilities their designer originally wanted (Brown, 1983). It is also worth pointing out that this restoration of a reasonable hull form did not change the rest of the design, which remained too congested to readily facilitate technology insertion and provide additional ship services.

2.3 TYPE 22 COMPARED TO TYPE 23 FRIGATES

A similar contrast can be drawn between the Type 42's ASW consort, the Type 22, and the latter's eventual successor, the Type 23 Frigate classes (Purvis, 1974, Thomas & Easton, 1988). Despite some initial constraints, the Type 22 was conceived as a proper replacement for the LEANDER Class as the main ASW Frigate in the fleet and was designed with healthy margins and a spacious layout. This initially resulted in senior naval criticism that it was an under-armed ship for its size, in a very similar manner to the criticism of the SPURANCE Class in the U. S. Navy when they were first introduced into service (see Section 2.6). However, the contrast in the relative ease with which the later batches of the Type 22s were stretched and considerably enhanced with vital new sensors, serves only to highlight again the short sightedness of some senior decision makers, with a lack of understanding of ship design. In the case of the Type 23 Frigates, the responsibility for yet another design "without any margins" lies in a combination of the unusual origin of the design, not as the Type 22 Replacement but as "a towed array Tug", plus the extremely fraught political environment in which the design evolved. The operational requirement was also justified, more so than for earlier designs, by the extremely specific (TA operations) OA modelling referred to in Section 1. That OA on which the ship design drew was then made redundant by the fact that the Cold War ended before the First of Class entered service. The final flaw in the overall procurement concept for the Type 23 was that the design should be marginless, which was directly attributable to the top-level decision to make this class have a service life of only 18 years. The fact that the remaining ships of the class are, currently, looking to some 30 years typical service life only reinforces the need for intelligent ship design knowledge to be given reasonable weighting in top level procurement decision making. In the case of the Type 23 short life decision all those involved at the concept design level knew that this decision would not be adhered to but were unable to convince the policy makers to restore adequate margins. The through life cost implications can be squarely laid at the altar of political interference in ship design matters.

2.4 R.C.N. ST LAURENT CLASS

A contrasting design to the "marginless/non adaptable ship" is provided by Baker's St Laurent design produced when he was in Canada in the 1950s (Baker, 1956). He not only provided adequate margins in the design, which enabled the ships to subsequently accommodate a very large helicopter on a relatively small ship, he also adopted a "Stylised" layout. This clearly delineated the various compartments in a given category (i.e. Payload, Living, Working, Services, Liquids) from the other categories, thus ensuring, as in the case of the Counties above, that the considerable inboard impacts of subsequent technology insertion were achieved with minimum disruption to the rest of the existing ship fabric. The design, like the Type 22, was readily modified in later batches to accommodate enhanced weapon fits. It is also relevant that, with a more generous beam than the contemporary British designs (Brown, 1983), the inevitable degradation in statical stability righting lever, due to top weight growth, was more readily accommodated, thus justifying Baker’s design insight and strong design control.

2.5 THE CAH INVINCIBLE CLASS CARRIERS

An example of an adaptable ship at the top end of the warship spectrum is that of the INVINCIBLE Class Carrier. The concept of this design developed out of that of an ASW Helicopter Cruiser, which because of its large helicopter complement and the clear intent to make its through deck and hangar able to operate VSTOL aircraft, was quickly modified into a small but genuine aircraft carrier (Honnor & Andrews, 1982). Large warships designed to carry and operate several aircraft or amphibious forces and vehicles have, by virtue of the volume and deck area required, inherently adaptable configurations. Thus the INVINCIBLE Class have been modified over the years to accommodate considerable enhancements in their aircraft, combat suite and complement. This has been due principally to three features consciously incorporated in the design. Firstly, generous margins, not just in stability but also in structural and ship services standards. Secondly the General Arrangements exhibit a sophistication in balancing the many demands of general access, storing, removal routes, escape routes, weapon handling, command and control, aviation support and damage control with the major constraint of a long hangar and flight deck – see Figure 1 (Honnor & Andrews, 1982). Finally from the start of the ship design, the major aviation features (hangar and lift dimensions, hangar and flight deck structural design) were designed with technology insertion in mind. This was done by avoiding the expedient of just designing for the current generation of aircraft, rotary and VSTOL, but rather for the expected next generation of both types, including allowances in the ship’s structural scantlings and generating capacity. These seemingly generous margins have enabled the adaptation and useful life of these vessels to be extended and this philosophy has been also been adopted in the RN's Future Carrier, despite its main design intent being to maximise sortie generation rate as the prime requirement (Knight, 2009).

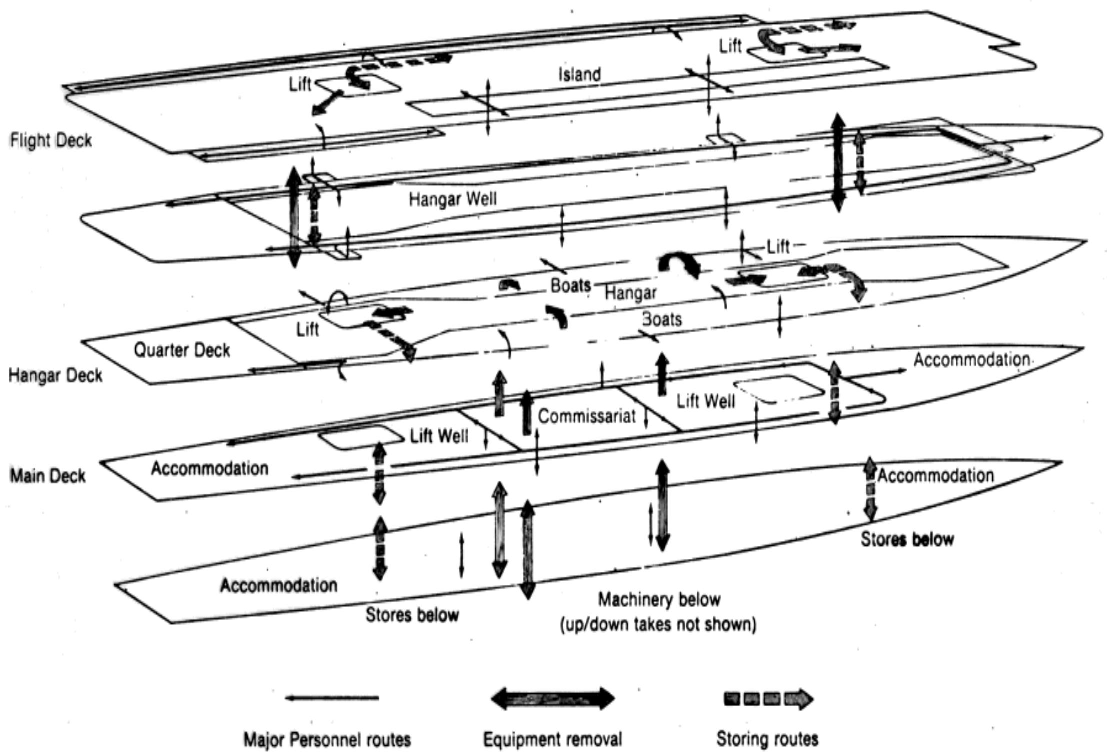

Figure 1 The INVINCIBLE Class Carrier Layout Logic
(Honnor & Andrews, 1982)

2.6 U.S.N. SPRUANCE/KIDD/TICONDEROGA CLASSES

The final example of an adaptable design is that of the U.S. Navy's DD963 or SPRUANCE Class (Leopold & Reuter, 1970). This whole class was procured under the Total Package Procurement policy of Secretary of Defense McNamara, with a strong through life support incentive on the contractor Littons. Leopold therefore built into the design not just very generous margins but also left significant portions of critical compartments, such as the CIC (Combat Information Centre, namely the Operations Room in UK parlance), empty and labelled as "Reserved for future equipment". These ships were initially criticised in the fleet as being under armed at 7700 tons deep displacement. However the design proved to be highly adaptable such that a more heavily armed version (initially for Iran then incorporated in the U.S. Navy as the KIDD Class) completed at 9200 tons, and the ship design was then used for the Aegis Cruisers, CG 47 or TICONDEROGA Class. However, as Table 1 shows, this final extrapolation was not in the end a success, as the first of this latter class was completed without the equivalent of the UK Board Margin (see Section 4) thus having "no margins for future characteristic changes" (Watkins, 1982) and too close to its structural and damage stability limits at the start of the design's service life. This sounds very like the fact that the CG 47 team, in focusing on the high-risk development of the Aegis AAD component of the project, had forgotten to build in even minimal adaptability to the ship. Thus the lead combat system engineers did not address the whole system of systems that constitutes a warship (Andrews, 2011).

Table 1: Chronology of Design Growth in US Navy Combatants

SPRUANCE			
	on completion(1)	Displacement	7700 tons
		Complement	240
		Accommodation	296 (20% growth allowance)
	growth	Displacement	8000 tons
	'in a few years'(2)	K.G rise	0.3 ft
		Manning	36% increase
KIDD			
	on completion(3)	Displacement	9200 tons
TICONDEROGA			
	contract target(3)	Displacement	9200 tons
	on completion(3)	Displacement	9500 tons
	with minor payload additions(3)	Displacement	9600 tons
	'naval architectural limit'(3)	Displacement	10,200 tons

Notes:

1 Collins (1975)
2 Keane (1982)
3 Watkins (1982)

3. MODULARITY CASE STUDIES

As early as 1971 the then Advanced Ship Concept Team in the US Navy's NavShips (now NAVSEA) in a paper entitled "A Philosophy of Naval Ship Design and Construction" examined the "broad construction philosophy of modularity" (Spero et al, 1971). Figure 2 taken from that paper shows the concept for "single mission escort ships" with exchangeable "functional payloads" for AAW, ASW and shore bombardment. This was a very putative concept and a much more substantive US version of Modularity was shown by Broome & Friedman (1992) looking generally at Future Combatants. Figure 3 from their paper is entitled a Variable Payload Ship, which they describe as designed "for ease of change during construction and service life". They remark that such vessels are likely to be larger than present designs, however "sheer size does not entail higher cost". This does not seem to have been borne out as the current set of combatants have got larger without any noticeable reduction in outfitting costs, which still seem to be priced on historic weight based initial cost (Andrews, 2018a).

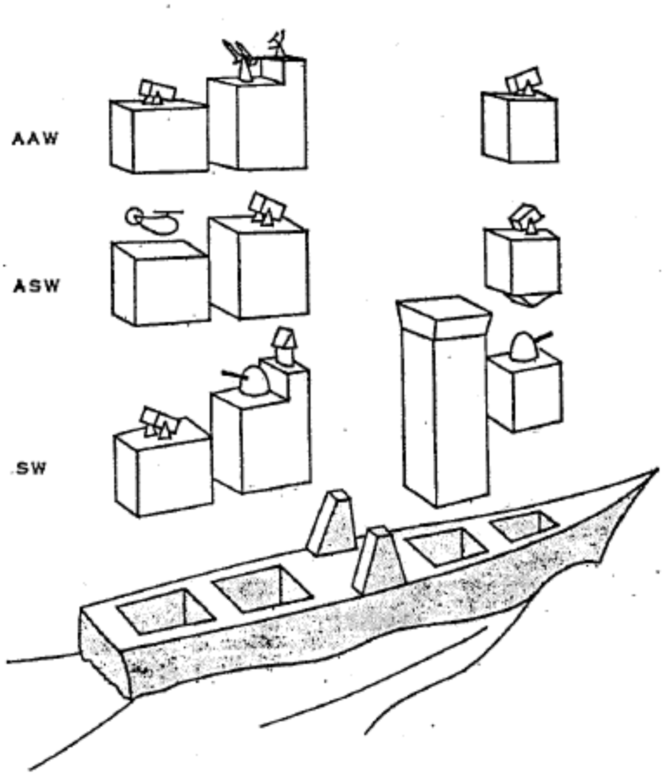

Figure 2 US Navy Modular Escort Ship Concept

(Spero et al, 1971)

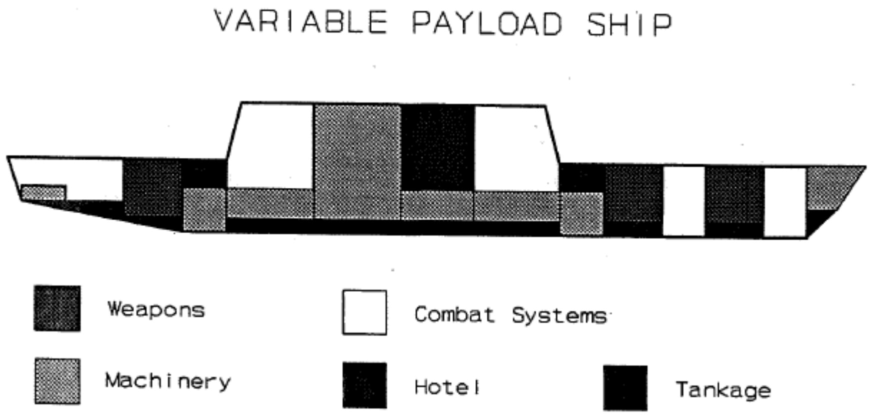

Figure 3 US Navy Variable Payload Ship concept

(Broome & Friedman, 1992)

ARAPAHO (Betts & Harris, 1984) was a NATO project which Modularised the provision in standard 40ft. T.E.U.s of all the requirements to operate and sustain 4 SeaKing ASW helicopters fitted to a containership to provide emergency convoy defence. The full capability provided of flight deck, hangar, accommodation, weapons, C3, servicing, on-board logistics and additional power, required 73 specially outfitted 40ft. T.E.U.s and 92 modules (for the hangar and flight deck structure). After the first ship set was manufactured and trialled at sea the follow on provision of sets for an adequate number of convoys to be protected was not proceeded with. However the exercise clearly demonstrated that modularising (even with the physical convenience of attachment to container ship spigots) is extremely space inefficient compared to "traditional integration" of combat systems into warships. Proponents of Modularity are likely to respond that this can be balanced against the expense of outfitting naval combatants both on build and in any upgrading through life – however through life cost savings are less easily argued through defence acquisition bureaucracies and short term revenue focused politicians.

Two systems that are said to be modular that have gone to sea in significant numbers of hulls are the Blohm & Voss MEKO system and the Danish Navy's smaller (coastal craft) STANFLEX approach. Both systems were pertinently discussed by Figg (1994), when addressing "Affordable Warships". The MEKO system concentrates on "modularising" major weapon equipment (such as whole gun emplacements), provoking Figg's comment "little thought is given to (ship & propulsion) systems being integrated". STANFLEX has been subsequently adopted in larger ocean going vessels (e.g. HMDS ABSOLOM) where a large mission bay can more readily accommodate different modules from the STANFLEX range.

The UK Cellularity approach was fully detailed by Gates (1986) as an attempt to standardise, in "cells", the electronics hardware. Since that was seen as the key upgrade/adaptability issue for electronics (which change so rapidly), rather than addressing the rapid replacement of the weapon delivery components of the combat suite. That it did not get adopted by the R.N. at that point was seen at the time as due to a lack of whole ship vision across naval procurement, combined with the then appropriate combatant design (the Type 23) being conceived as a single role (Towed Array ASW) vessel design with short life, margin-less and cost (UPC) capped. Thus the ship project refused to have a small increase in volume for Cellularity capability, in part hard to demonstrate with the pre-architectural numeric based concept design practice (Andrews, 2003). This then resulted in a potential fleet wide through life opportunity being lost.

It might be argued that the most successful implementation of container based mission bays has been the US Navy's LCS classes of fast mono-hull and trimaran combatants, certainly true numerically since vessels are still being added to the US Fleet. However the programme has been somewhat disastrous (see article in Warship Technology, 2016) and in this instance it could be argued has meant the effectiveness of clearly demonstrating modular payload adaptability has been missed, or at least confused, by the design conflict arising from the (questionable) very high combatant speed (50knots "desirable") demanded by the requirements owner (OPNAV).

However, a paper by Courts and Broadbent (2018) to last year's Warship Conference, summarising a series of studies by BAE Systems and UK MoD (DSTL), shows that the attraction of "Adaptability, Flexibility and Modularity" remains. That paper gives a comprehensive set of definitions and structured aspects where these three characteristics (or Styles, see Andrews (2017)) can be addressed for their advantages and disadvantages in being adopted in future naval combatants. It is not appropriate to repeat their paper's detailed presentation, which is very coherent and sets out to clarify what can be seem to be an ill-thought through bandwagon. That the paper also addresses the "optimisation" of Fleet Structure, as part of the "modularity" debate, indicates the need to make such "Style" choices beyond individual ship programmes (in contrast to the Type 23 above). This further, but rightly, complicates early stage ship design (ESSD) decision-making (Andrews, 2018b).

4. THE ISSUE OF MARGINS IN THE DESIGN FOR ADAPTABILITY

In the above examples of adaptable warship designs the term "margins" has been used to characterise, to a significant degree, the provision for adaptability. The consequences of deliberately omitting margins for Adaptability through life, in order to meet the political constraint of minimum initial cost, can be seen in the example of the Type 23 as already described. While the US Navy example of the CG 47 in Section 2.6 shows that exploiting an initially adaptable design can only be taken so far, as the issue is not simply accommodating predictable weight growth and the rise in the ship's centre of mass. It is the case that it is also necessary to retain a sensible reserve of space and other ship features to be adaptable. While it may not be the whole story on adaptability, the issue of what is meant by margins in naval ship design needs to be appreciated as a major part of the issue. What initially follows is essentially the UK practice as the approach adopted by the U.S. Navy uses a somewhat different terminology (Gale, 1975).

The concept of margins in warship design is quite sophisticated as there are essentially three distinct sets of margins. Only one of these is primarily concerned with adaptability, that one known in UK practice as Board Margin(s), which reflects that the level of Board Margin to be provided in a RN ship has traditionally been in the gift of the Admiralty or Navy Board. Whether that is strictly still the case, following a series of organisational and process changes, culminating in the Smart Procurement Initiative (UK MoD, 1999), is debatable; however the point being that these margins are in the gift of the operational requirement owner (i.e. the naval staff), rather than the designer, at least as far as intent, if not implementation. Of the other two categories, the first, Design and Build (or Contingency) Margins are required through out the design and build process to allow for uncertainty in the design, as it is being developed to its definition on completion and these should all be consumed once the ship's fabric and equipment is manufactured and installed. These margins, essentially in weight, space and location, provide sensible budgets for the various sub-system designers to work within. These margins reflect uncertainty and without them the overall design balance of the ship would not be maintained and redesign would be necessary late in the design and, furthermore, the conclusions of the earlier cost-capability trade-offs invalidated.

The other category, being that of Growth Margins, is often confused with the Board Margins as it might be seen to imply that it is something to be traded off to enhance the initial capability. This is a profound misapprehension, as Growth does not refer to growth in capability, which might be defrayed for enhancing current capability, but rather allows for unplanned growth in a warship's weight. Such growth has been seen to occur in warships over their operational lives, at a clear, measurable and reasonably constant manner. Without incorporating these margins in the design, the ship will only meet its stability, structural strength and powering standards and requirements on build. This would have grave consequences, either for ship safety or the operational freedom of the ship early in its life. It would almost certainly preclude any meaningful consideration of upgrading the operational capability - rather the opposite. However there is a clear need for the requirements owner and the ship designer to understand what is a sensible design point in the intended life of the individual ship beyond which at least some degradation in performance, if not in inherent ship safety, is acceptable. If this is not done then effectively the ship will spend the bulk of its existence over designed. The normal way out of this bind has been to plan on a mid life modernisation, one element of which is restore the ship back to safety standards for the remainder of its planned life. In this way Growth Margins are only required until this modernisation, however approaches such as Progressive Upkeep if adopted will mean this should not be so likely to be easily accomplished. Finally, it can be seen that while Growth Margins do not provide for Adaptability, they are intimately linked to that provision and that there needs to be coherency in the application of both sets of margins.

So the Board Margins can be seen as an additional provision for future equipment and, very importantly, that equipment's likely impact on the overall ship design. Given the future equipment will demand space (often high in the ship), add weight, require additional crew, ship services and even enhancements to ship's structure, then the overall impact may be far greater than the direct physical attributes of any, currently speculative, new capability. It can be seen from this that those highly adaptable designs already discussed, by virtue of their generous design features, have been able to effectively exploit their Board Margin provision. Conversely, ships like the Type 42 just to maintain vital standards, required considerable additional refit work to install new capabilities. Furthermore incorporation of vital upgrades has been extremely expensive due to the knock on effects, which have required major work to restore standards, usually at the loss of some performance in, typically, speed, endurance and seakeeping. So Board Margins, while seen as essentially weight and stability (and possibly space) provision for future capability enhancement, should be combined with a sensible margin in other critical features of the design, such as local structural features and ship services. If this is not done, this may result in too much of the Board Margin provision being absorbed by the wider consequences of installing a reduced level of new equipment. This will then mean that the extent of capability upgrade possible could be noticeably reduced.

The US Navy's (NAVSEA) practice on ship design margins differs, at least in terminology, from the UK's approach, above, and it is worth pointing out some differences if only to understand Table 1 above, which has been re-produced here as it provides such a clear and salutary example. US Navy practice was summarised several decades ago by Gale (1975) and that paper is still pertinent. Thus "Future Growth Margins" are seen as specifically for Adaptability and then split into (OPNAV specified) FGM (equivalent to UK Board Margin) and "service life growth" (equivalent to UK Growth Margin/Design Point). The dangers of overly focusing on the weight and KG implications of adaptability is shown by the consequences of the mid-life upgrade of the USS Franklin Delano Roosevelt (FDR). Blisters were added to the hull to "restore GM" after a major refit to accommodate the latest aircraft. Unfortunately, the additional GM was excessive and the carrier was too stiff in roll motion to then operate the aircraft. The issue with GM (often not realised by non-naval architects) is that it has to be sufficient for stability but still relatively small to avoid roll resonance. Given it is also the difference of two large numbers then a relatively small percentage error in either can lead to too little or (in the FDR case where the Chief Engineer of the Navy was sacked) too much GM.

However getting design provision for adaptability is not just weight, KG and space, it is also having sufficient margins in each of the distributed ship service systems (DS3). Any DS3 provision for adaptability can be hard to allocate early in the design, yet beyond that additional demands to the DS3 are difficult to meet and can have extensive “knock-on” implications. Current research, sponsored by US Navy Office of Naval Research (ONR) at several universities, including the author’s research team at UCL (Brefort et al, 2017), are looking at better sizing and routing of DS3 in ESSD. Electrical load growth to accommodate adaptability demands is another tricky design call, which may be eased in the next generation of naval combatants given fuller all-electric power schemes (IFEP) with more flexible installations.

5. DESIGN FOR ADAPTABILITY

Considering wider ship design related issues relevant to adaptability, beyond the crucial issue of margins, there are both generic combat system issues and others that might be better considered as more directly ship design related. However, any sharp division into combat and ship “halves” of the whole system of systems constituting a highly integrated modern warship runs the danger of falling into the bad design mind-set of “payload” and “platform”, which was roundly dismissed in the introductory remarks in the author’s paper at last year’s Warship Conference (Andrews, 2018a).

5.1 COMBAT SYSTEM ASPECTS

Many current weapon systems have some degree of modularity/adaptability through being made to interface with ship elements, such as silos. Future systems such as Directed Energy Weapons (DEW) are likely to be seen as more integrated with regard to components beyond the delivery elements of ordinance in silos, as shown by Figure 4 taken from the UCL DEW investigation (Andrews et al, 2011). The fit shown in Figure 4 is for two DEW units (a Free Electron Laser and a Long range Rail Gun) showing how they would be traditional installed – but could be readily modularised (and with sufficient adjacent space provision for future upgrades). DEW ship fits are likely to have a clear synergy with Integrated Full Electric Power (IFEP) installations already being proposed to “eliminate the tyranny of the shaft line” (Andrews et al, 2004). The ability the latter gives to placing prime movers and other major power distribution components in other than the traditional machinery spaces also opens up the possibility of more readily modularising such items. This is because they can be placed higher in the vessel with ease of such modules being more readily replaced, as is seen with the QEC carriers (Eddison & Groom, 1997) in comparison the complex removal lift arrangements for deeply located diesel generators in the previous INVINCIBLE Class (Honnor & Andrews, 1980).

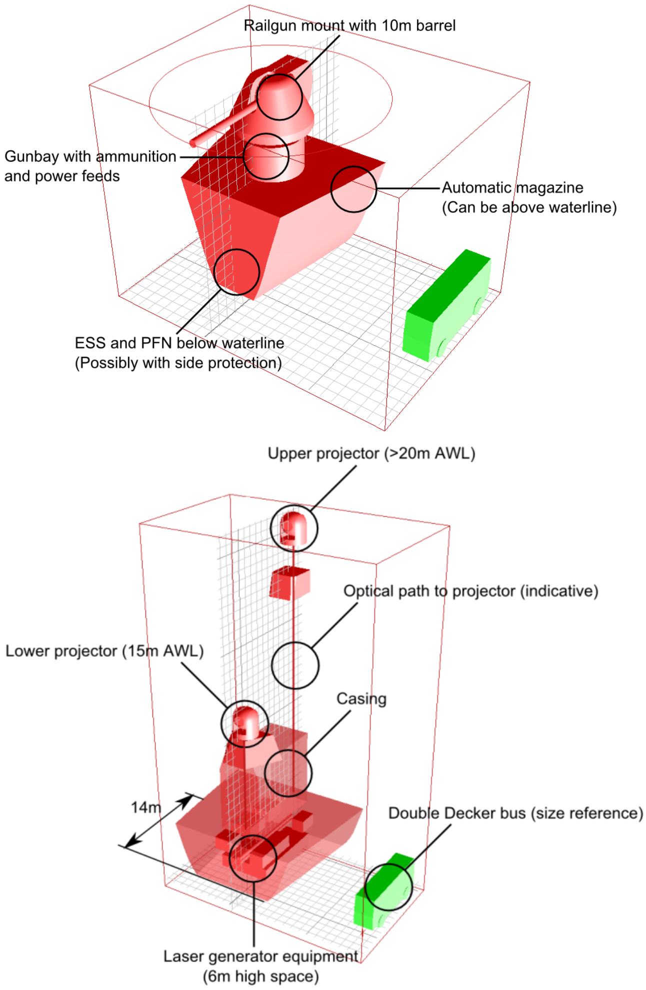

Figure 4 Generic weapon system layouts for a DEW Cruiser design
(Andrews et al, 2011)

It has long been recognised that even the helicopter version of organic aviation, while giving naval combatants state of the art ASW location and prosecution capabilities, imposes a major ship fit demand on relatively small vessels, especially as the helicopters get bigger and the supporting features also seem to expand – see the Merlin implications on the Type 23 Frigates. (An excellent outline of such ship fit demands was provided by Farrell et al. (1971) where two SeaKing ASW Helicopters were incorporated into the design of the Tribal Class (DDH 280) for the R.C.N.. Those authors concluded that such a fit dominated the aft half of that ship design.) If accommodating one large helicopter is combined with several unmanned air vehicles (UAVs), which are likely to be more regularly up-dated than manned rotary aircraft, then the case for providing adaptability to the aviation support features on-board would seem to be very strong. Whether this means modularising every part of the aviation outfit, given the ARAPAHO experience outlined in Section 3, seems questionable.

Another capability to be considered here, even if not solely arising from direct combat system related up-grades, is that of the adaptability of personnel provision onboard. While the ARAPAHO experience would seem to rule out "containerising" personnel accommodation demands, on the basis of excessive spatial demands for the relative small naval combatant, making the ship more adaptable to take likely increases in personnel provision as part of adaptability needs to be addressed early in an "adaptable" ship design. While there are on-going efforts to reduce warship's complements through automation (such as the step change for the US Navy with the Zumwalt Class) the earlier examples of both the USN FFG7 escorts and the R.N. Type 23 Frigates (see Andrews, 2018a) of arbitrary accommodation limits, mandated "to keep down initial procurement costs, run counter to achieving a coherent measure of adaptability.

5.2 SHIP RELATED ISSUES

Court and Broadbent's (2018) consideration of the related issues of Adaptability, Flexibility and Modularity led them to conclude that the intentions behind these related initiatives were best described by six classic (naval) ship design transversals (or "ilities"), which they call "Desirable Characteristics" and are included in this author's macro and major Design Style aspects (Andrews 2017). Courts and Broadbent's "six" are Producibility, Operability, Supportability, Flexibility, Re-configurability and Adaptability. This author would like to just briefly address (from a Design for Adaptability consideration) Producibility plus two other "Style" or transversal aspects, that of Survivability and the related issue of Stealth. The latter doesn't easily become an "ility" and, incidentally, spans the (artificial) divide of combat system and "the rest" of the warship.

Stealth might be readily seen as contributing to Survivability but raises specific design issues with regard to achieving Adaptability. The easier set of stealth aspects to address, in this regard, are those associated with above water signatures. In particular radar cross section signature levels, vital to ensuring anti-missile decoys are effective require the above water external structural shaping to avoid right angle corners and planes to be some 7 degrees out of the perpendicular. This is an issue if an adaptable solution is makesrecourse to containerisation or non-RCS compliant modules exposed to missiles using radar seekers.

However a more fundamental ship design implication arises with underwater signatures, the key to ASW (Hamson, 2016). If a naval combatant is to be a truly effective ASW vessel then it must be designed from the very beginning with minimising underwater signature as a key design driver. Achieving this requires a comprehensive approach, not just for the hull form and appendages (hydrodynamic flow, particularly at key sonar operating speeds and not just at maximum speed for which the hydrodynamics of warships are usually "optimised") and the propulsors in the hull's wake (again specific speeds are crucial) but also **any** significant machinery on-board (particularly those low in the hull with noise paths that may need remedial attention up to and including "double acoustic mounting"). Although most of the final signature profile will need addressing right through to the detailed design stages, without the overall "Style" right from design commencement reflecting this major design driver, a first rate ASW capability cannot be achieved. From an adaptability stance any up-grade or new ASW sensor is hard to predict and, even if the design is generous, likely to be hard to incorporate.

Survivability (for a through consideration see, Piperakis et al, (2014)), particularly the Vulnerability component, could be said to be the traditional feature that distinguishes the warship from the merchant vessel, yet interestingly is not in Courts and Broadbent's (2018) six Characteristics. What Vulnerability means for an adaptable design can be considered in two parts:-

Firstly, the level of resistance to major damage designed into the ship must be maintained as the features incorporated for adaptability are (rightly) exploited through life. Thus margins provided for weight and KG would include provision for still achieving the "design intent". This can lead to an interesting challenge as "excessive" initial margins on weight, space and KG might mean, for a considerable part of its life, that the ship is (apparently) "over designed". It can also raise the question as to what design condition is the ship being designed to meet – that before its "adaptability" has been used or later in life having been up-graded. What price then the measured mile on acceptance or initial manoeuvring trials?

Secondly, if the design (as UK combatants should) incorporates the very effective but demanding feature of NBCD zoning (incorporated firstly post the Falklands Campaign in the Type 23, see (Manley, 2001)), this can present some difficulties if adaptability is achieved through adopting a large mission bay (as in the Type 26). A potentially large mission bay, such as that shown in Figure 5 (from Kouriampalis, (2019)), that might straddle two zones could invalidate substantial (double bulkheads) zone boundaries, or result in USS ZUMWALT like size of combatant that very few navies could contemplate (see concluding remarks).

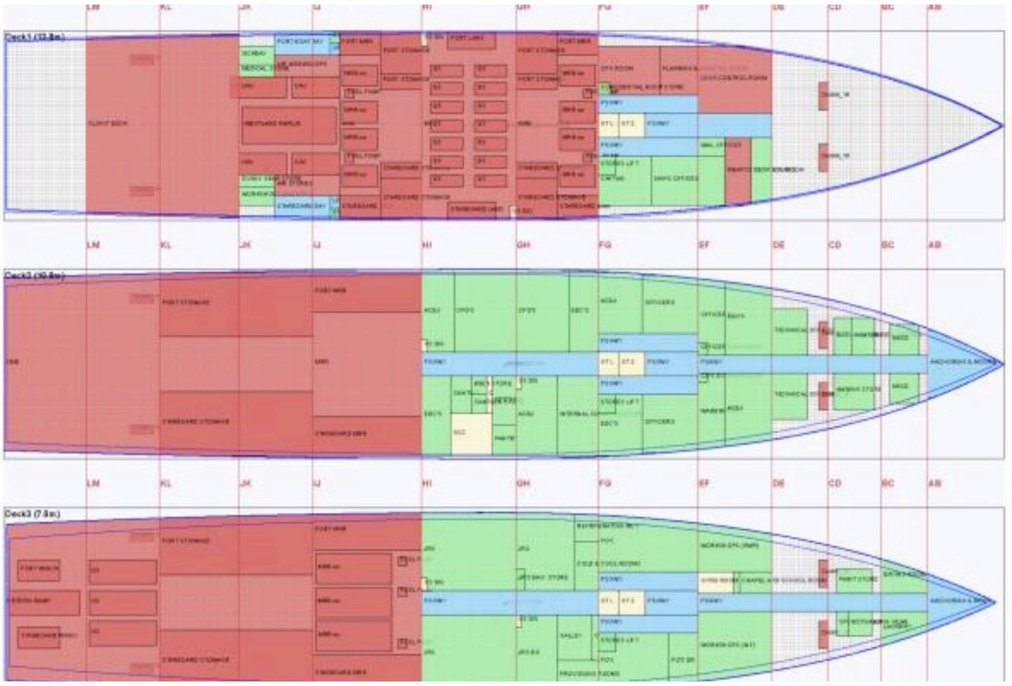

Figure 5 Study for a UXV Mothership showing how large Mission Bays

can drive up ship size

(Kouriampalis, 2019)

Producibility has been a warship design Style issue that has arisen from concerns with affordability (Keane & Fireman, (1993), Andrews et al, (2005)), however, a focus on initial procurement cost (UPC in UK terms – see the conclusion of Andrews (2018a) for a critique of UPC as a measure of affordability) can be seen as inconsistent with keeping the overall fleet expenditure down. Building into a class of new naval vessels the virtues of Adaptability, as propounded by the theme of this conference, is likely to be in direct conflict with Producibility. This is in part due to the latter currently being measured, in ESSD, by largely weight based (and historically derived) costs, which see the "smallest" ship solution as best meeting UPC "minimisation". This obviously penalises incorporating such measures as adaptability margins and features requiring inherently "generous" designs, so revealing little regard for the subtleties of reducing through Life Costs.

In concluding consideration of Design for Adaptability, it is relevant that Courts and Broadbent (2018) explore the topic by looking at "Fleet Structure" rather than at a single ship class that has a particular policy mandated to be applied separately to each warship IPT Leader. Courts and Broadbent present Benefit vs. Cost Pareto Fronts for some five parameters, but still use UPC for the cost measure. A concluding result from these initial studies seem to be that a sub-set of capabilities in multi-purpose vessels is "more cost-effective" (albeit with the above cost limitations) than smaller role specific or even larger "fully flexible" vessels. However, this is said to apply only if multi-purpose means general escort and other (minor) roles, rather than prime Force capabilities, such as ASW and AAD. An issue not explored by this MoD sponsored study is whether major "Ship Style" options (Andrews, 2018b) might realise the benefit if they were to be configured for Adaptability, even in the case of the top end combatants that Courts and Broadbent seem to rule out. One noticeable option in this regard is considered in Section 6.

6. TRIMARAN – THE ULTIMATE ADAPTABLE COMBATANT

The 2001 paper (Andrews, 2001) presented a review of likely hull configurations as part of a survey of trends in warship design. It is not intended to repeat that review here but rather to point out that some eight configurations were compared with the mono-hull for nine aspects which had previously been considered to be the basis, in general, for comparing different hull forms for a naval combatant (LRS, 1988). Clearly the choice of aspects is debateable and, in any particular new design, those most relevant to its emerging operational concept and acquisition constraints will actually determine the assessment of the relative merits, rather than necessarily those shown in the table, which are of general applicability. It is noticeable that the nine (LRS) aspects did not explicitly include that of Adaptability or, indeed, Modularity. Although adaptability could be said to be implied in the final aspect in Table 2 of through life costs, it has been considered from early on under the S^5 item of Style by the author (Brown & Andrews, 1980) and recently expanded upon, (Andrews, 2017). A more explicit set of aspects could be the High Level Characteristics (derived under the UK's Smart Procurement Initiative), which were adopted for the RN's Future Surface Combatant (Andrews, 2000). The FSC, as the precursor to the Type 26, was seen to have seven High Level Characteristics, three of which were directly missions related, Warfighting, Power Projection and Utility, while the others were considered to be enabling, namely, Interoperability, Sustainability, Survivability and, most significantly for this paper's theme, Adaptability. Thus Table 2 has the additional aspect of Adaptability in addition to the 2001 version.

Table 2 Qualitative Assessment of Different Hull Forms

Aspects \ Ship Types	Mono-hull	Cata-maran	ACV	SES	Hydro-foil	SWATH	HY-SWAS	WIG	Trimaran
Speed, Power and Endurance	Good	Good[1]	V Good[2]	Good	V Good[2]	Good	Good	V Good	Good
Space and layout	Good	Good	Ave	Good	Poor	V Good	Poor	Poor	V Good
Structural design and weight	V Good	Ave	Poor	Poor	V Poor	Ave	Poor	V Poor	Good
Stability	Good	Good	Good	Good	Good[3]	Good	Good	Poor	V Good
Manoeuvrability	Good	Ave	Poor	Good	Good	Ave	Good	Poor	Good
Noise, Radar & Magnetic Signature	Good	Ave	Good	Good	Good	V Good	Good	Good	V Good
Weapon placement & effectiveness	Good	Ave	Ave	Ave	Poor	Good	Ave	Poor	V Good
Construction costs and build time	V Good	High	V High	High	V High	Good	High	V High	Good
Through life costs	Good	Ave	V High	High	V High	Ave	High	V High	V Good
Adaptability	Good	Good	Good	Good	Poor	Good	Good	Poor	**V Good**

Notes.

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

What might seem remarkable from the, admittedly qualitative, exercise comparing the various hull configurations summarised in Table 2, is the very impressive score of the Trimaran configuration, even compared to the mono-hull, which has been the invariable choice for all, except the most operational specific naval vessels. This latter fact has been due to the mono-hull being an inherently mission flexible hull form able to undertake most naval roles with more than reasonable facility. The current paper argues once more that the Trimaran has the potential to replace the mono-hull as the most effective configuration for the warship of the future, not just because of the assessment suggested by Table 2, but specifically because it provides, more readily and with less design impact, those features that are required for Adaptability. Unlike the other configurations compared in Table 2, the ocean going Trimaran combatant is essentially a relatively minor departure from the mono-hull (Pattison & Zhang, 1995). It has many features in common with the mono-hull and can draw on the proven technology applicable to mono-hull warships, unlike most of the more advanced forms in the comparison. That the only extant Trimaran combatant, the US Navy's LCS variant, is more technologically radical than the original UK concept (realised in the two-thirds scale demonstrator for the Trimaran option of the FSC, R.V. TRITON (RINA, 2000)) more due to the high top speed sought for the LCS than its trimaran configuration.

There are considered to be two aspects in the overall design nature of a mono-hull warship that noticeably restrict its ability with respect to the need to provide an adaptable design. They are the ability to cope with maintaining adequate stability with subsequent technology insertion and providing sufficient space on the upper works and main deck(s), especially amidships. These aspects are necessary to achieve an adaptable design but there are also other aspects, which have been mentioned earlier. The origin of the Trimaran came from a desire to separate the traditional dichotomy in the mono-hulled warship, that is to achieve the necessary stability, particularly with the growth in top-weight with the ever increasing demand for higher and larger sensors (such as the Sampson Radar so significant in the Type 45), while requiring a long fine hydrodynamic form to minimise installed power at high speeds. The Trimaran achieves the latter by providing a very fine main hull and the former by the relatively small side hulls, which by virtue of their wide separation, provide sufficient intact and damage stability required for little immersed displacement. Furthermore, the Trimaran can do this more effectively than the mono-hull as the latter is limited to that moment gain which is set at its design freeze, whereas the Trimaran can if necessary accommodate any reasonable level of rise in top-weight. This can be met by relatively minor modifications to the side hull separation. It amounts to effectively a tuneable feature through out the ship's life - a characteristic providing noticeable KG margins for adaptability only when required.

However, adaptability also requires internal space precisely where in a mono-hull "real estate" is most competitive – high in the hull amidships, where generosity in space provision is sensible if an adaptable design is to be achieved. Thus the Trimaran's cross deck structure, linking the three hulls, provides the ideal configuration for an adaptable ship. In sizing a new Trimaran design, one of the major design decisions concerns the wet deck clearance, from still water to the underside of the cross structure (Andrews & Zhang, 1995). This gives the designer essentially excess volume in the ship, relative to the mono-hull equivalent, in the cross deck structure, at amidships and high in the ship. With the weather deck above the cross structure being considerably wider in the middle third of the Trimaran it can much more readily accommodate large hangars located with the flight deck close to the ship's pitch centre, a feature very hard to achieve in a mono-hull. Additionally, as Table 2 indicates, the Trimaran also scores well for other issues identified as crucial in achieving an adaptable warship, readily meeting the survivability, supportability and producibility features better than its mono-hull equivalent.

With these advantages one might question (even with the (slightly odd) example of the US Navy's high speed Trimaran LCS Class) why the Trimaran has not been seriously pursued in recent R.N. combatants, given the R&D lead UCL and the UK MoD established in the late 1990s. The case for the Type 45 being trimaran configured might just be countered by its parallel design development in that period, although the author (reinforced by his personal involvement in both programmes) considers the lack of consideration more due to MoD "handing over" Design Authority for the Type 45 to its Prime Contractor (Gates, 2005) as symptomatic of procurement policy overriding design clarity (Andrews, 2018a). The case for the Type 26 to be trimaran configured seems even stronger with the FSC concept explorations (Andrews, 2000) and, arguably, **the** design driver being Adaptability. Again there was a degree to which the procurement policy decided not to explore this potentially advantageous novel solution post FSC, where the mind-set appeared to be overly risk adverse. This might be perpetuated in the current competition for the Type 31e "Exportable" light frigate, despite the above arguments that if you want Adaptability (say for export customers with differing requirements) a highly adaptable design should be a winning one. If a Trimaran combatant can give multirole adaptable solutions for relatively low risk, why have we not been able to move on from operationally "optimised", initial cost constrained and highly tuned design solutions to now design and build truly adaptable warships for an uncertain future?

7. CONCLUSIONS ON MULTI-ROLE AND ADAPTABILITY

It would seem, in meeting the needs of multi-role capability, that adopting adaptability characteristics is likely to be the way forward, but this is far from straight forward since the main issues and conflicts this paper has identified need to be addressed from the very earliest in the combatant design process. The author has recently argued (Andrews, 2018b) that the ESSD for complex vessels, such as naval combatants, is sophisticated and must not be rushed through "to get on to design proper" (i.e. post the concept phase). Some of the issues raised in this paper reinforce the need for sophistication in deciding whether to adopt a typical major Design Style issue – that of Adaptability.

This sophistication means exploring, in a given new naval vessel programme, the implication of the desired level of Adaptability on the various consistent capabilities (such as Courts and Broadbent's "six Desirable Characteristics" plus other "transversals", such as have been discussed in this paper). Secondly, the exploration should include a comprehensive consideration of the solution space (Andrews, 2018b) as this could reveal better means of meeting the perceived needs for the new programme. An indication of thinking "out of the box" has been given by consideration of the adaptability of the trimaran configuration in Section 6.

Nevertheless, pursuing the full capable multi-role warship solution can run the risk of ending with a single affordable "Starship Enterprise" (Kirkpatrick & Pugh, 1982) so there is a need to ensure coherence between solution and requirement in producing a balanced design. In this instance one with sufficient Adaptability, taking cognisance of the historical examples of First Rate options and avoiding spurious "optimisation", such as the Type 23 as a Cold War GRIUK Gap concept being then used as a general ocean going combatant, while ensuring Adaptable designs can be pursued. That this is best done by consideration of novel solutions, which might be battle winning over safe (non-risky) designs ought to be part of a properly conducted ESSD process (Andrews, 2018b).

8. ACKNOWLEDGEMENT

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