Important Trends and Junctures in Warship Design - Redux

By the Editor – In building a capable navy most countries opt for proven designs rather than resourcing R&D, overseeing detailed contractor designs, and building up shipyard capability. But, as the authors argue, those countries are not benefiting from long-term savings by being able to perform their own conceptual designs. Such organic design would enable them to build better their warships based on their specific areas of operation and corresponding threats. A fuller version of this paper was first published in a fuller form in the Journal of Marine Systems & Ocean Technology, *27 Apr 2020*[1]

Introduction

To build up a capable Navy, most countries would procure proven designs rather than providing significant Research and Development (R&D) allocations, oversee detailed contractor designs, and build up shipyard capability. The reasons for this predilection are likely to be attributable to both collective and individual factors; such as a lack of knowledge, limited design experiences, concerns about cost estimates, uncertain results and slow investment returns. Some countries arguably do not consider fully and strategically how much they would save long-term from being able to perform their own conceptual designs. Such design would then enable them to build better their warships based on their specific areas of operation and corresponding threats.

The *Oliver Hazard Perry-Class (FFG-7)* is highly representative of an incremental design approach that the US Navy applied to ship design and construction. Although, the FFG-7 was designed and then built in large numbers of 'low-mix' systems it was based on a goal known as 'design to cost' and was for low-threat environments (United States Navy, 1974; Francis, 2005). The strategies used for this design involved both significant R&D allocations before construction and included detailed design specifications for contractors. Criticised at the time for being under-armed and lacking in redundancy, this class was not regarded as being part of President Reagan's 600 ship Navy. Nonetheless, its conceptual design space (CDS) created a fundamental break with pre-existing designs. Consequently, it was more representative of the Information Age (1970-2015), into which it was conceived in the mid-1970s, than the Industrial Age (1920-1965) designs that preceded it.[2]

By contrast, an examination of submarine build programmes where there are regularly refreshed conceptual designs and more modularised build and construction, show submarine Basic Mass Empty (BME) costs[3] have generally remained below those of other weapon systems. Such BME costs have only increased at, or below, historical inflation. In simple terms, submarines usually have become more affordable, not less, and this is reflected in countries like Thailand, Indonesia and Myanmar actively seeking such capabilities.[4] Theoretically, surface warship BME costs should have kept pace with submarines – but they have not. In actuality, frigate and destroyer numbers have often halved over the same period, meaning that unlike submarines, surface warships have generally become less and not more affordable.

Nearing the end of the *Information Age*, the authors submit that a reconceptualisation of the warship design space; shipyards and build techniques – a revolution in warship design – is probably overdue.[5] Fundamental shifts in the political, economic and military affordability of ships and potential warfare losses appear necessary to improve the efficacy of Naval surface warfare.

Background

Mario Bunge, when addressing the failures of individualism, attests "knowledge is social."[6] If this is the case, a revolution cannot occur without the human factor. It is human art, skill, and designs that are used in the formation of science: a synthesis to deal with new concepts and ideas, expressed in various forms of models and other abstract forms including mathematics; with the technologies derived from them. Taking the two precepts together, it is possible to conclude that "Knowledge is social and the technological also."[7] Based on these analyses, since the British Industrial Revolution, there have been five identifiable scientific ages, such that a new age could be imminent.[8] Kossmehl (2009) traces the history of the first synthetic materials and

Period	Scientific Age
1770-1815	Steam Age
1820-1865	Locomotive Age
1870-1915	Turbine Age
1920-1965	Industrial Age (as recognised in the literature)
1970-2015	Information Age (as recognised in the literature)
2020-2065	Synthetical Age

Fig. 1: Different Ages as defined by the Science Time Constant (45-50 years), with the gaps between ages defined by chaotic states as one age dies.

proposes these as the starting point for a 'Synthetical Age' where the artificial outweighs the natural world. Reay Atkinson et al.[2,6] describe why they posit the new age should be called the Synthetical Age.

The Dreadnought Revolution (1906) was based on Parson's development of non-compounded steam turbines and, specifically, the introduction of a vacuum (1900-1904) that quadrupled thermal efficiency.[9] Marder argues that "at the turn of the [19th] century ideas on naval tactics began to emerge from their chaotic state."[10] These states of "successive growth stages of cascading logistic curves; [connecting] natural growth and chaos like states,"[11] typically occur at the end of an age when a system comes off-line. Although the 'Turbine Age'[12] had some years to run (with the development of end-tightened blading (1918-1930)), by the beginning of the 20th century, it was coming to its end. A new critical juncture was forming with the onset of the 'Industrial Age', leading to mass production, tanks, turboprop, jet aircraft, and aircraft carriers. The German and Imperial Japanese battle doctrines of *Blitzkrieg* and *Kantai Kessen* were based to an extent on mass-produced turbines.

Towards the end of the 'Industrial Age', in the 1960s, similar chaotic states were emerging and leading, on the one hand, to the revolutionary designs behind the McDonnell Douglas *F-15 Eagle* (arising from the remarkable Skunk Works), nuclear-powered attack/deterrence submarines and, on the other, to the *Oliver Hazard Perry (FFG-7)* Class. The sinking of the Israeli warship *Eilat*, in 1967 by the Egyptian Navy, is considered as the primary thrust for developing the Anti-Ship Missile Defense Program (ASMD) within the US Navy. Thus, the *FFG-7* was designed and provided with anti-ship missiles, anti-aircraft and anti-submarine guided missile to provide the open-waters escort of amphibious task groups; e.g. warfare ships and merchant ship convoys:

"The Israeli CNO Admiral Yohai Ben Nun placed great emphasis on sophisticated equipment – essentially dividing naval content (weapons, sensors, crewing etc.) from the hull (sometimes considered as the platform). After heated debate, it was decided that the 'boats' (subsequently to be known as Missile Boats) should be based on an existing hull or platform whose operational functionality had already been proven in a [West] European country. It is not clear whether or not Yohai envisioned the vessel in detail. However, his staff made a huge effort to take forward his design thinking. They were aware of the miniaturisation process evolving in technology and electronics. They therefore decided to adopt the concept of designing highly sophisticated smaller [missile] 'boats', each capable of working alone or networked, and supporting electronic systems picture to shape the tactical moves and develop firing solutions, in advance."[13]

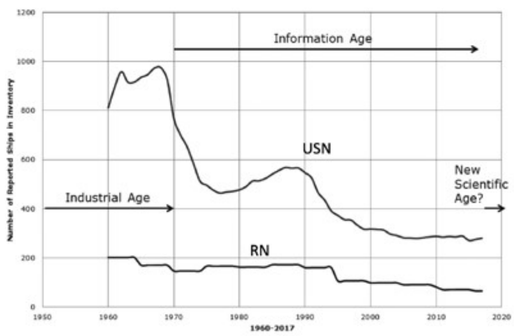

Fig. 2: USN & RN fleet sizes (U.K. MoD, 1995)

Golding in Reay Atkinson *et al.*[3] writing in *Versatile Modular System designs for a Versatile Modular Fleet*, concludes that there are peacetime and wartime builds. This phenomenon appears to be evident in meta-analyses of recent defeats and victories examined by Biddle (2004) and concepts like the Revolution in Military Affairs (RMA) when rapid-evolutionary (and revolutionary) technological and organisational changes occur in warfare.[14]

Through policies such as *Front Line First*,[15] the formal end of the Cold War in 1992 led to reductions in Fleet sizes (see Figure 2). Also, the UK R&D budgets were reduced by as much as 85% in real Defence cost inflation terms between 1979 and 2008.[16]

The cost imperative of conceptualising and creating new designs removes or significantly reduces Defence cost inflation from the system. As recognised by Pugh (1986, 2007) and Augustine (1997), by creating new designs, one begins again.[17] In other words, the replacement designs for the UK *Type 22* frigate, itself very similar in design and concept to the *FFG-7*, were not optimised versions of older designs, such as the *Leander-Class*. Instead, they maintained inflationary adjusted unit costs; designed and conceptualised anew to maintain numbers.

Current Trends

Without investment in new designs, concepts and strategies, inadequacies in equipment had to be compensated for by better-trained people, and, in conflict, by urgent operational requirements. Cuts to research budgets correlated to the failure to invest in a revised frigate programme in the UK, US, other NATO countries and Australia through the 1990s, when the emphasis was also placed on maintaining status-quo designs. For example, three Australian classes of warship programmes approved between 2003 and 2004 were all based extensively on re-designs. The designs were the ASMD-enhanced ANZAC Class (incorporating CEAFAR phased array radar), the Air Warfare Destroyers (*Hobart-Class*) and the *Canberra*-Class Landing Helicopter Docks. The cause of such re-use, it is argued, lay in the structural shift between investing in, or abstracting, new designs and optimising existing or status quo ones. The enablers to critical deeper thinking, being research and education, were not used or were “drowned out.”[18] This potential illusory thinking of saving money and time is most recently evident in the Canadian decision to look for an existing frigate design.

The global stagnation of Defence research and development, outside of a few critical areas in the US and China, is apparent in reviews like Bitzinger.[4] Specific to maritime, Bitzinger covers the US Navy *DDG-1000* program and attempts at new destroyer and cruiser designs (*DD-21* and *CG-21*). He cites Luttwak[19] as concluding that, “instead of shaping new platforms and weapons configurations to fit today’s information technology, communications, sensor and guidance equipment, we are shoving, cramming and moulding such technology to fit the nooks and crannies of 1945-era platforms.”

In seeking to explain the reasons for stagnation and re-use rather than innovation, he references Kaldor,[20] asserting that, “…military bureaucracies, being naturally ‘conservative’ and operating according to ‘dominant scenarios’, are not really comfortable with radical new technologies, since they ‘pose a risk for organizational survival.”

Kaldor herself states, “New technologies can only get through the innovation and integration stages if they conform to the requirements of the dominant scenario… directed towards the improvement in performance of missions that were established nearly 40 years ago…”

Pugh[17] observes, “We are at a turning point in the history of Defence. Future generations of combat [fleets] are unaffordable for any save the USA. Major changes to the landscape are inevitable.”

The tightly coupled Optimised Design Space is based upon enforcing evidence-based performance constraints and transaction history. It generally predicts outcome – more-for-less – and does not account for alternative empirical concepts; experiments; experiences or existences.

It can also remove variety, reflection, possibilities and 'plausible alternative concepts' from designs. As identified by Modis,[11] systems coming 'off load' show hysteresis, identified in the wide swings in BME costs of latter *Type 23s*, and seemingly in Average Procurement Outlay per Delivery (about an average of about $4bn) variations, amplified (60 times) shown in Figure 3.[21]

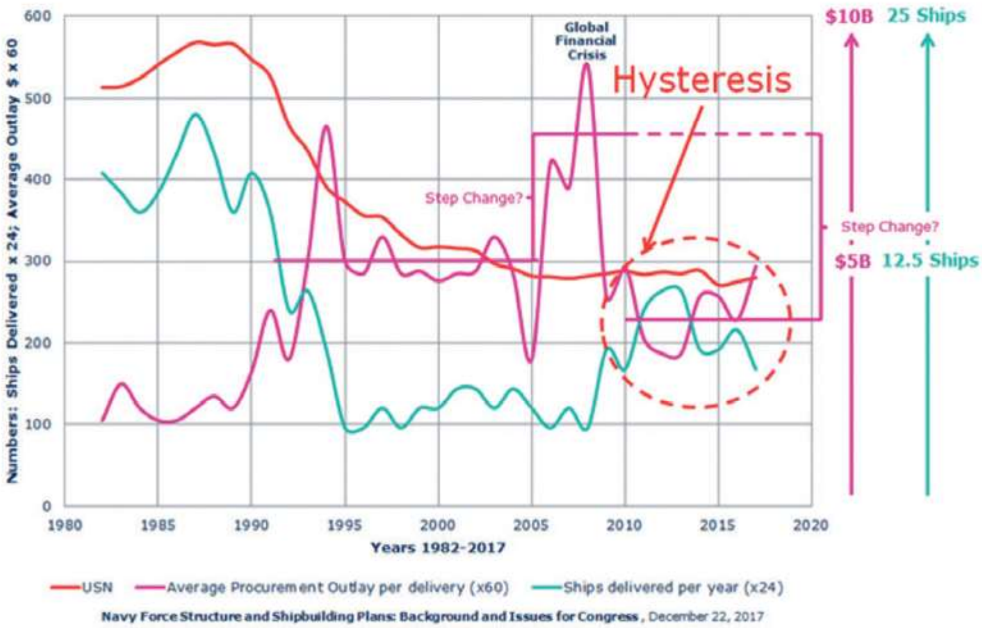

Fig. 3: USN Fleet Size; Ship Deliveries and Average Procurement Outlay per Delivery, estimated/abstracted from Kirkpatrick (1995), Hall (2017) and Richardson (2016)

The position arrived at may be unstable, unsustainable and, ultimately unaffordable in political, military and economic terms (even for the US). More demanded from even less to the point, potentially, of *reductio ad absurdum*; sweating assets and people at the expense of readiness and productivity.

High-level Strategies

High-level strategies to enable a fundamental shift in warship design could include:

- **Abstracting, conceptualising and creating new designs – new conceptual design spaces.** This design approach is advocated. The revolutionary designs of *FFG-7* (and UK *Type 42s* and *Type 22s*) were not reconceptualised and maintained in the early 1990s, due to the peace dividend and the end of the Cold War. Combined with a new scientific age, a revolution in naval affairs (RNA) is in the offing.[5]
- **Reconceptualising and redesigning** existing classes and combinations/compositions of systems / capabilities / platforms. For example, the UK's HMS *Ocean* (L12) designed to commercial standards came in at the same mean unit cost of the *Invincible*-Class carriers built 20 years earlier.[16]
- **Maintaining a regular refresh and build rate – tempo.** This approach requires a

programme connecting design and conceptualisation if one is going to change from one generation to the next continuously.

- **Spending much, much more** (power-law increases in budgets) to maintain/preserve existing (obsolescent) design and build capabilities, e.g. the *Type 45*, the *Zumwalt*-Class, or Australia's *Hobart*-Class. This approach is the risk the Australian Navy faces in a premature down-selection for SEA 5000, which was one of the reasons the *Hunter*-Class variant of the *Type 26* was chosen. However, by cost and BME, the *Hunter*-Class remains a derivative of the US's *FFG-7* and the UK's *Type 42*.
- **Stop and get off**, as the Royal Navy appears to have done. Even if the *Type 26* GCS were truly an innovative and impressive design, its prospects would be hobbled by the decision of the Cameron government to go back on its plan to buy 13 of them (replacing 19 *Type 22* and *Type 23* frigates). Instead of purchasing eight anti-submarine versions and five general purpose versions, the government is now committed to buying just eight ASW frigates. This is fewer than a traditional ship class and that matters because you need to commission and build at least ten vessels to be able to assess their real abilities (to distinguish good, from poor, from average) and make appropriate improvements.[22]

This research re-examined the revolutionary aspects of the *FFG-7* warship design to provide more strategic detail to these high-level design strategies. These aspects are presented in the next section, followed by a contemporary reflection of each of them.

The Revolution that was *FFG-7*

The *FFG-7* class frigate was for the USN a revolutionary 'design-to-cost' program designed to compensate for dwindling numbers of anti-submarine warfare escort ships with which to protect convoys such as supply to NATO or for US amphibious task forces. The *FFG-7* class was explicitly not required for escort of carrier task forces, for which the more capable and more expensive *Spruance*-Class *DD-963* destroyers were acquired in a similar time frame (from the late 70s through early 90s). The cost criterion also extended to the numbers of ship's force and air detachment personnel to be accommodated. The corporate mantra was the 'High-Low mix' approach mandated by the then US Chief of Naval Operations, Admiral Elmo Zumwalt, quoting Soviet Fleet Admiral Sergei Gorshkov who proclaimed, 'Better is the enemy of good enough.' *FFG-7s* were to be "expendable tin cans." It was notable in Australia's *Collins*-Class submarine program that this approach was not followed with the predictable result that corrective actions spanned more than a decade following construction.[18]

For each *FFG-7* ship, there would be a period of shakedown and acceptance trials after delivery, followed by a post-shakedown availability (PSA) when corrective actions would be programmed. The lead ship, the USS *Oliver Hazard Perry*, was also be subjected to class design evaluations of a formal operational test and evaluation when fully configured and to a whole-ship shock test.

The importance of the land-based test sites in managing revolutionary designs is captured by Stark and Stembel[23] as follows, and is in stark contrast to the Australian experiences of the Collins Class Submarine a decade later[18] and the Landing Helicopter Dock ships only a few years ago:[24]

"Although costly to design and to build, these two test sites were of inestimable value in accelerating the Lead Ship design and the FFG Program. The Propulsion LBTS [Land Based Test System] permitted ordering and testing of the gas turbine, reduction gear, shaft, propulsion control console, and associated lube oil system more than a year earlier than would otherwise have been the case. Similarly, early development of the Combat System LBTS forced decisions on equipments and arrangements and made data available much earlier than normal. As a result of the two test sites, data for these systems were never a problem in the Lead Ship design, and the successful Acceptance Trials of *FFG-7* were attributed in large measure to these Facilities.”[23]

Revolutionary Trends in Military Research and Development Effecting Next FFG Design

To see where the next innovative FFG design might come from requires two significant steps. First, to remove from consideration all recent warfare where naval forces were arguably only an enabler of majority land conflicts and held mostly by one side only. Second, to step away from platform-thinking to systems-thinking, to see where technology can go if unconstrained. Taking the first, the last naval engagement between near-peer adversaries, where these engagements seriously shaped the outcome, was the Argentine-UK Falklands War in 1982, 35 years ago.[25]

Predominately Forcing	Forcing and Enabling
Over-the-horizon Radar (OTHR)	Electronically Scanning Array (ESA) radars
High-Frequency Surface Wave Radar (HFSWR)	Ship-borne sonar-arrays, hull-mounted & towed
Hypersonic missiles, including long-range aircraft-launched (Kemburi, 2016)	Unmanned Underwater Vehicles (UUVs) & Unmanned Aerial Vehicles (UAVs)
Cyber-warfare (Joiner & Tutty, 2018; Heinl, 2016)	Cyber-security (Joiner, 2017; Joiner, Atkinson & Sitnikova, 2017)
Ocean-bottom & tethered remote-sensing sonar arrays	Information dominance (networking plus cooperative engagement)
Highly programmable sea mines employed analogously to improvised explosive devices	Unmanned surveillance & maritime patrol aircraft
Submarine endurance from nuclear or air-independent propulsion (Raska, 2016)	Active stealth vice passive reflectance & absorbent designs
Submarine stealth	Swarming of unmanned vehicles, counter-measures or weaponry
Space-based persistent infra-red sensing	Intelligent Integrated Platform Management Systems (IPMS)
Cyber, Bigdata, Artificial Intelligence, and Quantum AI (QAI)	Remote situational awareness to hardened command centres
Laser weapons	Tactical nuclear weapons
Lightweight armour made of composite materials	Anti-ship ballistic weapons

Fig.4: Critical Emerging Technologies effecting naval ship design, especially in Asia-Pacific

With the recent identification of Russia and China as the primary competitive forces for the West to address, the emphasis is again onto the redesign of surface warships to meet 21st century adversarial capabilities. In particular, the expected widespread use of autonomous unmanned vehicles (AUV) is highly likely to change dramatically the design of the operating and support platforms from which the AUV will operate. Bitzinger4 also points to Chinese R&D as the most influential in defence innovation: “…this possible ‘lull’ in disruptive strategic innovation… may provide a pause or slow-down in the global process of defense technology development that would permit latecomer innovators and ‘fast-followers’ to draw nearer to the state of the art. This is particularly apropos in the case of China. China has… increasing military expenditures at least five-fold over the past 15 years… its defense R&D, although classified, probably approaches $6 billion annually… Certainly, in its pursuit of a fifth-generation fighter aircraft (e.g., the *J-20* and the *J-31* prototypes), it is poised to overtake Europe in this one particular area.”

The final trend to cover is that of cybersecurity, where arguably the pursuit of information dominance has led to an inevitable counter of malicious use of the cyber-domain.[26] Heinl[27] points out that: “…acquiring offensive or advanced cyber capabilities could seem financially attractive, in particular for less wealthier states in the [South-East Asia] region, relative to the higher costs of other weapons… defence analysts predict that many South Asian states will undertake state-sponsored cyber programs facilitated by low barriers of entry, the availability of large pools of skilled manpower and extensive IT infrastructures.”

Envisaging Revolutionary Warship Designs

Against a *first-world* contender, "to survive in the modern battlespace, Fleets will need to be able to afford to take the hits and the losses."[3] Therefore, losses will need to be politically, militarily and economically affordable if ships are going to be used, such as was epitomised in the design approach of the *FFG-7* class. This section examines the main contemporary design influences for greater affordability in the context of warship attrition, then how these influences might be modularised and conceptualised to create the new design spaces and to envisage impacts on crew and fleet compositions. The section then examines the cultural influences that have constrained more affordable attrition before concluding with key recommendations and the associated high-level design criteria.

Contemporary Design Influences. In projecting the emerging military technologies on future surface warship design to provide for greater attrition, the following salient design influences are emerging.

Modularising. Blake, in a *New Model Navy*,[28] considers the need to move from 'crewing the equipment', to 'equipping the crew' – a long-standing criticism by Army (and Marines) of navies and air forces. This paradigm shift would be a fundamental change in procurement and acquisition doctrine, training and education; emphasising the agility of crews to think through and solve problems tactically, and the fidelity of the system to enable operational

CURRENT POSITION	ASSUMPTION	DEDUCTION
Improvements to networking cross-spectrum sensors, including sonar, electromagnetic & from satellite & cyber tracking of resources (i.e., logistics chains/information/big-data flows)	A Fleet Vessel will be detected at some stage of an operation	Stealthy hulls are of less value & the expensive premium paid for quiet hull/tiles etc. may not be justified against a *first-world* contender
The threat posed by conventional weapon systems like cruise & ballistic missiles of *first-world* adversaries is such that even the largest vessels will not survive a hit. The threat posed by other anti-access systems such as sea-mines would disable most frigates & destroyers	Such weapon systems are not going to be used singularly but in salvos or fields	Scale counts. Either very much larger than current US aircraft carriers or many more frigates & destroyers are required to ensure the survival of the whole.
The affordability question becomes key to political, economic & military decision-making & taking.	The question is not whether or not losses are going to be taken – because they certainly will be – but what price each sector is likely to set	Political affordability (often tied militarily) can determine operational use. Numbers need to be both affordable (in build) & replicable in a timely way (during conflict) if they are going to have political value in conflict.
UAVs, USVs & UUVs are being pursued primarily to reduce risk to the up-front operator of systems – this includes smaller platforms, without life support & deck launch at much higher force.	Processing of data for these machines & the number of people necessary to maintain & operate these systems (from a distance), means a larger footprint. Alternatively, this requires a greater level of autonomy in the vehicle, which in turn requires a level of trust regarding both effectiveness and ethical behaviour.	For real-time processing of data, such processing power may need: a) to be closer to the operation, & b) more influenced by humans in the real-time loop. Local, as opposed to remote, mobile platforms capable of piloting UAVs & assessing/processing data becomes more critical.

Fig. 5: USN Fleet Size; Ship Deliveries and Average Procurement Outlay per Delivery, estimated/abstracted from Kirkpatrick (1995), Hall (2017) and Richardson (2016)

versatility and strategic adaptability.[3] At its heart, this is what we envisage by the Versatile Modular Systems approach to conceptualising, designing, building and crewing affordable and sustainable future navies.

Conceptualising Design Spaces. Considerations set out in this paper, have concomitantly led to the development of consolidated deductions for conceptual design space for warships, as set out in Figure 5. Blake[28] also stipulates as critical, the management of the flows of systems, crews and materiel between the Navy, its Auxiliary and Support elements and the Merchant Marine. He envisages the capitalisation and rescaling of Naval and Auxiliary Fleets through the application of 'fit-for-purpose', versatilely modularised merchant hulls – in a way also to grow and sustain (red flagged) merchant marines and ship-building industries.[3,28]

Cultural influences. Another way to deal with attrition is to revisit paradigms for setting fleet (and so crewing) numbers. First, consider the cultural paradigm that set fleet numbers in the 'Information Age.' The Cold War threat equation believed that threat was equal to capability plus intent and will. Because capability could be objectively measured (in terms of numbers of tanks, ships, aircraft etc.), it was. Ultimately, this over-concentration on capability led arguably to collective difficulties in anticipating and transitioning from the end of the Cold War and an over-reliance on information and technological dominance.

A fundamental design difficulty, introduced by 1990s reductionist and optimised design space thinking, was to confuse and conflate scale with numbers – as in numbers of ships and crew sizes. This difficulty was further compounded by an accountancy-based predilection conflating capability, with strategy; and ranking (ordering, controlling, tiering etc.), with positioning.[29]

Key recommendations and associated high-level design criteria. To develop novel conceptual designs of surface warships requires significant R&D allocations before construction and creation of smart naval ship design centres in parallel with smart shipyards that can produce needed equipment in terms of time, quantity and quality. Scalability and Composability become critical – which are as important political and economic considerations, as they are military ones.

'Versatile Modularisation', which is a form of agile adaptation, therefore becomes key.[3] The first Aircraft Carrier, HMS *Ark Royal*, was laid down in 1914 as a freighter, designed for the coal-grain trade in the Black Sea. More recently, the UK's HMS *Ocean* applied merchant-marine standards to achieve something of an affordable half-way house, between conflated Navy Engineering and Lloyds Standards, and a fully versatile modularised system.

Taken with the Army's long-standing criticism of Navies and Air Forces, that 'they man the equipment; rather than equipping the man', this suggests four critical design criteria that could improve naval systems thinking.

- First ask: 'what would we be doing, if we were at war – and, if not, why not?';
- Second, adopt the cult of the imperfect – sometimes adapted as 'second best, today': "give them the third-best to go on; the second-best comes too late, [and] the best never comes."[30] Remember what Admiral Gorshkov said "better is the enemy of good enough," with parallels to Voltaire of "not letting the perfect become the enemy of the good."
- Enable compositions for crewing the ship (and its unmanned vehicles that it operates and sustains); rather than shipping the crew;
- Scale capability-networks for fitting the kit; rather than kitting the fit.

Conclusions

A new conceptualisation of the warship design space; shipyards and build techniques – a revolution in warship design – is pressingly overdue. This juncture may be reinforced following the catastrophic sinking of the Norwegian Frigate, the KNM *Helge Ingstad* , following a collision in a Norwegian Fiord due (it is claimed) to a fundamental mismatch with the crewing current frigate designs.[31] Addressing the political, economic and military affordability of ships and potential losses is needed to shift the efficacy of naval surface warfare.

Capt Dr S Reay-Atkinson Ran, Capt C J Skinner Ran,
Gp Capt K F Joiner Raaf, Prof N H H Caldwell & Dr A Swindan

References

[1]Reay Atkinson, S., C.J., Skinner, K.F. Joiner, N.H.M., Caldwell, & A. Swidan. (2020). Important trends and junctures in warship design. *Marine Systems & Ocean Technology*, 27 Apr(https://doi.org/10.1007/s40868-020-00076-2).

[2] S. Reay Atkinson, C. Smallhorn, N. H. M. Caldwell and G. Tolhurst, Identification and Classification - Designing and Engineering Synthetic Ecologies, in *System Engineering, Test & Evaluation (SETE) Conference*, (SETE, Melbourne, 2016, pp. 128-142, ISBN: 9781922107824).

[3]See: P. G. Pugh, *The Cost of Sea Power*, (Conway Maritime Press, London, 1986) and S. Reay Atkinson, I. Hassall, N. H. M. Caldwell, M. Romilly and R. Golding., *Versatile Modular System (VMS™) designs for a Versatile Modular Fleet (VMF™) in paper presented at EAWWIV Conference*, (Old RN College, Greenwich, 2011).

[4]See: R. A. Bitzinger, ed., *Emerging Critical Technologies and Security in the Asia-Pacific*, (Palgrave Macmillan, Hampshire, 2016), pp. pp. 37-62, 91-106 & 154-166, and R. Maas, *Indonesian French companies join forces for naval projects, in United Press International,* March 31, 2017, http://www.upi.com/Defense-News/2017/03/31/Indonesian-French-companies-join-forces-for-naval-projects/9281490979577/:, accessed 26 April 2017.

[5]H. Riekhoff and T. Gongora, *Toward a revolution in military affairs?: defense and security at the dawn of the twenty-first century,* (Greenwood Press, Westport, Conn., 2000).

[6]M. A. Bunge, Ten Modes of Individualism - None of Which Works - And Their Alternatives, *Philosophy of the Social Sciences,* 30, 3, (2000, pp. 384-406).

[7]S. Reay Atkinson, *Engineering Design Adaptation Fitness in Complex Adaptive Systems, in CUED EDC,* (Cambridge University Engineering Department, Cambridge, 2012).

[8]See [2], [7] and Z. Hongzhou and J Guohua, Shifting of World's Scientific Center and Scientist's Social Ages. *Scientometrics*, 8, 1-2, (1985, pp. 59-80).

[9]C. H. Jr. Fairbanks, The Origins of the Dreadnought Revolution: A Historiographical Essay. *The International History Review*, 13, 2, (1991, pp. 246-272).

[10]A. J. Marder, *The Anatomy of British Sea Power*, (Alfred A. Knopf, New York, 1940).

[11]See: C. Marchetti, Fifty-Year Pulsation in Human Affairs, Analysis of Some Physical Indicators, *Futures*, 17, 3, (1986, pp. 376-388), and T. Modis, Fractal Aspects of Natural Growth, *Techno-logical Forecasting & Social Change*, 47, (1994, pp. 63-73).

[12]After J. P. Jarratt and P. J. Clarkson, *The surge-stagnate model for complex design. Journal of Engineering Design*, 13, 3, (2002, pp.189-196).

[13]N. Maor, Formation of Navy Part II - The Israeli Defence Force, 1960-1979. *The NAVY Magazine of the Navy League of Australia,* 79, 1, (2017, pp. 22-26).

[14]See 5., and S. Biddle, *Military Power: Explaining Victory and Defeat in Modern Battle*, (Princeton University Press, Princeton, 2004).

[15]See: U.K. Ministry of Defence (MoD), *Defence Cost Study (DCS): Statement on the Defence Estimate 1995*, Presented to House of Commons, (1995. Cm 2800, May), and U. K. MoD, *Performance Report:1995/96*, Presented to House of Commons, (1996, Cm 3448, November).

[16]See 2., 3, and S. Reay Atkinson, Design to Fight, *Naval Review*, (2008. 2, May).

[17]See: 3., N. R. Augustine, *Augustine's Laws*, (American Institute of Aeronautics, Reston, 1997); and P. G. Pugh, Retrospect and Prospect: trends in Cost and their Implications for UK Aerospace, *Defence and Peace Economics*, 18, 1, (2007, February: pp 25-37).

[18]K. F. Joiner and S. Reay Atkinson, Australia's Future Submarine: shaping early adaptive designs through test and evaluation, *Australian Journal of Multi-Disciplinary Engineering*, 11, 2, (2016).

[19]E. N. Luttwak, Breaking the Bank: Why Weapons Cost so Much, *The American Interest*, (2007. Autumn).

[20]M. Kaldor, The weapon Succession Process. *World Politics*, 38, 4, (1986).
[21]ESee: K. Hall, Costs of Building a 355-Ship Navy, in *Analysis for the US Congress*, ed. By Congressional Budget Office (CBO), (CBO, Washington, 2017, April); D. L. I. Kirkpatrick, The Rising Unit Cost of Defence Equipment - The Reasons and the Results, *Defence and Peace Economics*, 6, (1995, pp 263-288); and J. M. Richardson, A Design for Maintaining Maritime Superiority, Version 1, in *Strategic Assessment.* ed. By Chief of Naval Operations, (United States Navy, Washington, 2016, April).
[22]J. Foreman, The British Royal Navy - Road to Salvation, Part I, *The NAVY Magazine of the Navy League of Australia*, Apr-Jun, 2, (2017, pp. 12-17).
[23]R. E. Stark and D. M. Stembel, Detail Design-FFG 7 Class, *Naval Engineers Journal*, (1981, April: pp. 109-119).
[24]See: Australian National Audit Office (ANAO), *Test and evaluation of major defence equipment acquisitions, in Australian National Audit Office*, (ANAO, Canberra, 2015).
[25]I. Spellar, *Naval Warfare*, in *Understanding Modern Warfare*, ed. Jordan et al., (Cambridge University Press, Cambridge, 2016), pp. 159-226.
[26]K. F. Joiner and M. G. Tutty, A tale of two Allied Defence Departments: New assurance initiatives for managing increasing system complexity, interconnectedness, and vulnerability, *Australian Journal of Multidisciplinary Engineering*, 2018, http://dx.doi.org/10.1080/14488388.2018.1426407.
[27]C. H. Heinl, The Potential Military Impact of Emerging Technologies in the Asia-Pacific Region: A focus on cyber capabilities, in *Emerging Critical Technologies and Security in the Asia-Pacific*, ed. By R. A. Bitzinger, (Palgrave Macmillan: Hampshire, 2016).
[28]R. C. Blake, A New Model Navy, *Headmark: Journal of the Australian Naval Institute* 153 (2014, pp. 31-35).
[29]S. Reay Atkinson and A. Goodman., *Network Strategy and Decision Taking*. ARAG Occasional, UK Defence Academy, (2008. 11 August).
[30]Sir Robert Alexander Watson-Watt, KCB, FRS, FRAeS (13 April 1892 – 5 December 1973), pioneer of British WWII Radars.
[31]R. C. Blake, Flash Traffic: There seeems to be something wrong with our bloody ships today, and Under-Crewing / Investment in Frigates and Destroyers. *The NAVY Magazine of the Navy League of Australia*, 80, 1 (2019, pp. 19-21).