Important Trends and Junctures in Warship Design

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Abstract

Concerns about risks associated with new conceptual designs of surface warships have led many decision-makers to rely on the parent-design approach. For example, the design of the Oliver Hazard Perry Class (FFG-7) became the standard of surface warship design for 71 subsequent vessels in three Navies, e.g. Australia, Spain and Taiwan, even though the FFG-7 was initially considered under armed and vulnerable. This paper finds that following warship designs remain derivations primarily of limited parent-designs and that generally warship design is now increasingly costly, yet mostly stagnant, and with fleet numbers in steady decline. By contrast, submarine build programmes generally show regularly refreshed conceptual designs, new modularised build and construction, usually improving affordability and proliferation. Approaching a modern Synthetical Age, this paper submits that a reconceptualization of the surface warship design space, shipyards and build techniques are arguably at a critical design juncture. As such a revolution in warship design, like the FFG-7 design was, is overdue. This paper provides insights into the ship designs that are necessary and possible from today's emerging technologies. Such revolutionary design could inject greater usability and affordability to naval surface fleets and build more political, economic and military affordability of ships and potential warfare losses. This new approach is called 'Versatile modularisation.'

Keywords

Warship conceptual design space, revolution in naval affairs, critical emerging technologies, ship affordability, ship usability

1. Introduction

To build up a capable Navy, most Countries would procure proven designs rather than providing significant R&D allocations, oversee detailed contractor designs, and build up shipyard capability. The reasons for this predilection are likely to operate both collectively and individually, 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 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 Research and Development (R&D)

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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 (Atkinson et al., 2016).

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 (Pugh, 1986; Atkinson et al., 2011) 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 (Bitzinger, 2016; Maas, 2017). 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. Note, submarines and warships have very different design challenges, and so this cost comparison has accepted limits, and there are always exceptions to such generalised costings. The key here is only to examine and extrapolate the current trends and read-across the two vessel domains any useful precepts.

Nearing the end of the *Information Age*, the authors submit that a reconceptualization of the warship design space; shipyards and build techniques – a revolution in warship design – is probably overdue (Riekhoff & Gongora, 2000). 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.

This paper is structured first to provide some background on revolution design in general and for warship costing in particular. The current general state of warship design is then overviewed, leading to the hypothesis of five possible high-level strategies to fundamental shift what is considered a general stagnation in design. The paper then re-examines the revolutionary aspects of the FFG-7 design to determine possible detail to enrich those high-level strategies. Finally, the research article draws contemporary design lessons from the FFG-7, particularly for current technological trends. As such, this paper is meant to inform and provoke debate for professionals in any modern warship program.

2. Background

This paper has at its core the connective element between science, technology and the social. The combination of new science and new technology with the social aggregations of the time arguably leads to revolution. A revolution has at its core synthesis of all three: the social, the scientific and the technological. Mario Bunge, when addressing the failures of individualism, attests (Bunge, 2000) '*knowledge is social*'. 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. For example, in their examination of the British Aircraft Corporation's revolutionary 1960s TSR-2 strike and reconnaissance aircraft programme, Law and Callon (1998) concluded:

> *'… by following the technologists, we see the kinds of social worlds, institutions, and roles contained in the machinery they create. We also see the diverse objects mobilized to fit these conceptions. The technical thus is social'.*

Taking the two precepts together, it is possible to conclude that '*Knowledge is Social and the Technological also*' (Reay Atkinson, 2012). The linkage between the social and knowledge has been confirmed by researching past scientific and technological ages. In their examination of an earlier scientific age (Parson's Turbines), Jarratt and Clarkson (2002) and Reay Atkinson (2010) posited a scientific time constant, after Chen and Yi (2001), of 45-50 years for change to reach 95 per cent of its steady-state value (Reay Atkinson, 2012). These examinations also recognised that within the time constant, there also exist technological time constants (connecting the science) of about 15 years. Based on these analyses, since the British Industrial Revolution, there have been five identifiable scientific ages, such that a new age could be imminent (Reay Atkinson et al., 2016; Reay Atkinson, 2012; Hongzhou & Guohua, 1985). Kossmehl (2009) traces the history of the first synthetic materials and proposes these as the starting point for a 'Synthetical Age' where the artificial outweighs the natural world. Reay Atkinson et al. (2016) describe why they posit the new age should be called the Synthetical Age:

> *The argument developed in this section, is the evolutionary step change between the 19th, 20th and 21st Centuries which is represented by the non-divisibility of information from the technological. Every artefact – be it natural or human-made – can now be decomposed into its constituent information and then re-composed and replicated, for example through 3D printing. The divisible coupling between the information and the technological, that was applicable in the 19th and much of the 20th centuries, no longer applies – hence IT. Since IT is social and knowledge also, the primary coupling is between the social and the IT and the IT on the social. Nowhere is this more so than in Cyber.*

Reay Atkinson et al. (2016) goes on to propose that cyberspace and the people in it adapt over time in a '*synthetic ecology*' that ought to impact designs profoundly, such as with warships as offered here. Others like Preston's (2018) new book, '*The synthetic age : out-designing evolution, resurrecting species, and reengineering our world,*' extend the term to reflect on these synthetic effects to the world's ecology.

Table 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.

Period	**Scientific Age**
1770-1815	Steam Age
1820-1865	Locomotive Age
1870-1915	Turbine Age (as abstracted from Jarratt and Clarkson (2002))
1920-1965	Industrial Age (as recognised in the literature)
1970-2015	Information Age (as recognised in the literature)
2020-2065	*Synthetical Age* (as posited, Reay Atkinson (2012))

The Dreadnought Revolution (1906) (Fairbanks, 1991) was based on Parson's development of non-compounded steam turbines and, specifically, the introduction of a vacuum (~1900-1904) that quadrupled thermal efficiency. Marder argues that '*at the turn of the* [19th] *century ideas on naval tactics began to emerge from their chaotic state*' (Marder, 1940). These states of '*successive growth stages of cascading logistic curves;* [connecting] *natural growth and chaos like states*' (see Marchetti (1986) and Modis (1994), typically occur at the end of an age when a system comes off-line. Although the *Turbine Age* 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 miniaturization 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 and equipment with the ability for over-the-horizon picture forming and sharing the operational picture to shape the tactical moves and develop firing solutions, in advance.* (Maor, 2017)

Revolutionary designs for the Sa'ar Class, first demonstrated in the Battle of Latakia (1973), were scaled successfully into the FFG-7 class. Scaling included, for example, the embodiment of two heavy helicopters and their handling systems for sea-state six operations, gas turbine propulsion on a single shaft with controllable pitch propeller, and the operation with 30 less crew than previous manning formulae had required. Further details of the revolutionary aspects of FFG-7 will be considered later.

Golding in Reay Atkinson *et al*. (2011) writing in *Versatile Modular System designs for a Versatile Modular Fleet* (Reay Atkinson et al., 2011), concludes that there are peacetime and wartime builds. By this, he means that designs stagnate (Jarratt & Clarkson, 2002), atrophy and ossify in times of peace and often then fail in subsequent wars, such that new designs are then urgently required. 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) (Riekhoff & Gongora, 2000) when rapid-evolutionary (and revolutionary) technological and organisational changes occur in warfare. Consequently, nation-states need to maintain technological adroitness through periods of peace. Reay Atkinson in *Design to Fight* (Reay Atkinson, 2008) argued that without regular re-fresh and updating of the core design, fleets incur Defence Cost Inflation (DCI) (Pugh, 2007; U.K. MoD, 1995; Kirkpatrick, 1995); halving in size every 25 years. Both the Dreadnought and the FFG-7 Revolutions seemingly occurred at the change of scientific ages during '*chaos like states*'.

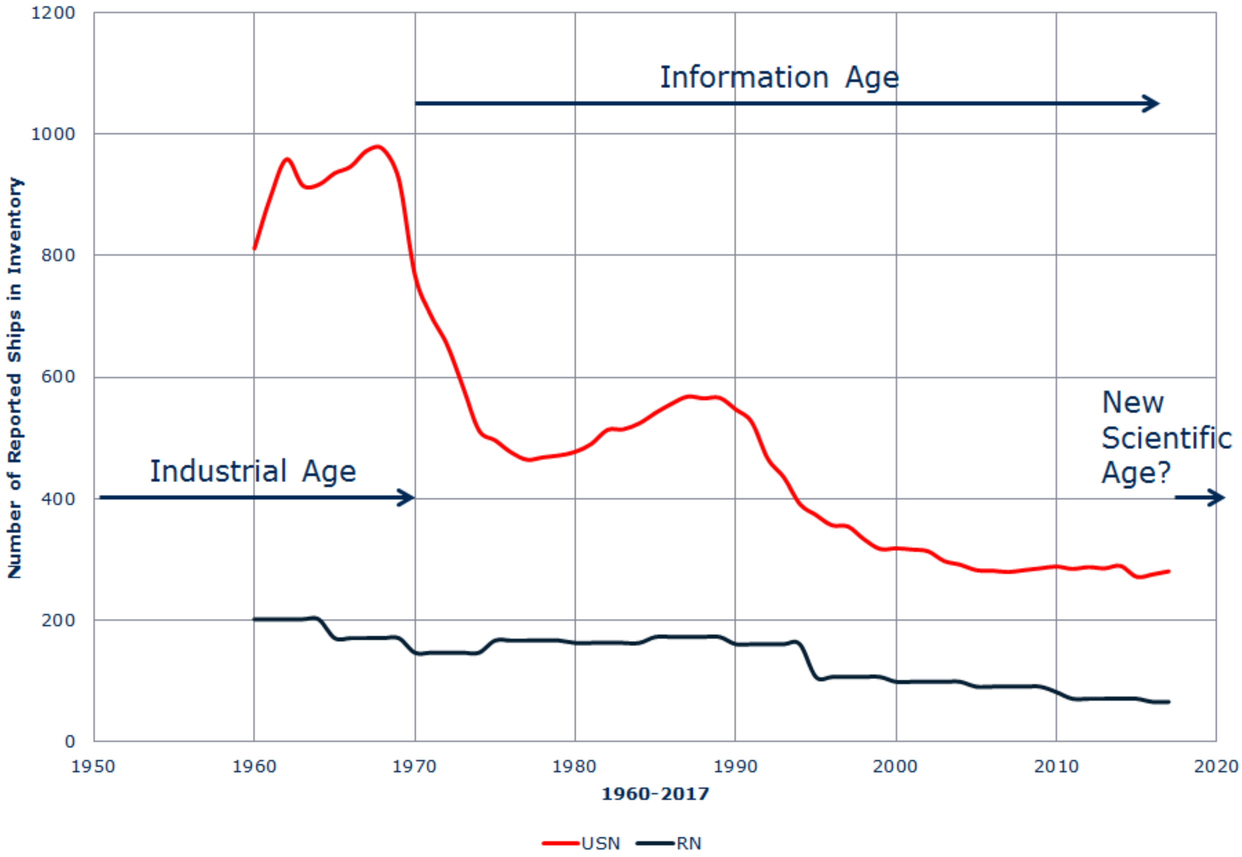


Figure 1: U.S. Navy (USN) and U.K. Royal Navy Fleet (RN) sizes (U.K. MoD, 1995)

Through policies such as '*front line first*' (U.K. MoD, 1995 & 1995/96), the formal end of the Cold War in 1992 led to reductions in Fleet sizes (see Figure 1). Also, the U.K. research and development budgets were reduced by as much as 85 per cent in real Defence cost inflation terms between 1979 and 2008 (Reay Atkinson et al., 2011; Reay Atkinson, 2012). Such reductions were similar in other Western Nations to a greater or lesser extent. Investment in training budgets fell slower than on procurement and research budgets and recovered more strongly post the 1998 U.K. *Strategic Defence Review* (to about 118 per cent its 1979 historical value). Following the unprecedented attack on the World Trade Center in New York (9/11), the emphasis was placed on operational training budgets, and investment has continued to grow faster in this sector ever since. Procurement budgets fell rapidly post-1992 before, in 1996, recovering to higher investment levels than for research budgets (U.K. MoD, 2010) – based on optimisation of existing designs, rather than creating new ones.

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. In other words, the replacement designs for the U.K. Type 22 (T22) 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. Based on the Basic Mass Empty (BME) costs of a 4500 Tonne Batch 1 T22 (~£19 per volumetric kg on build), a U.K. Type 45 (T45) Destroyer at 7500 Tonnes would have cost £146M in 1980. Based on historical inflation, the build costs in 2008 would have been about £550M (as opposed to £1 Billion). However, Pugh (2007) recognised that frigates, destroyers, main battle tanks and even nuclear-powered submarines (where the research was maintained) were attracting a BME cost inflation of only six per cent, '*one per cent above Historic Inflation*' between 1950 and 2008 (Joiner & Atkinson, 2016). In actuality, there was downward pressure on the costs of these items. New designs – significantly in commercial shipping – were beginning to drive down build costs. Adjusting for this downward pressure on historical inflation, a new T45 design in 2008 may have cost £410M: an equivalent 1980 BME of ~£14 per volumetric kg (Reay Atkinson et al., 2011).

3. 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 U.K., U.S., 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*' (Joiner & Atkinson, 2016). This effect was likely a collective reaction to past cost-overruns based on the questionable assumption that reusing an existing design would somehow restrict program cost and schedule growth. This trend was arguably misleading in procuring later batches of the UK Type 23 (T23) Frigates because they were primarily optimised versions of the T22; which is indicative of a system exhibiting chaotic states (Reay Atkinson, 2012). This potential illusory thinking of '*saving money and time*' is most recently evident in the Canadian decision to look for an existing frigate design:

> *Relying on a proven, off-the-shelf warship design from another country takes a lot of the uncertainty out of the planning process ... "We don't know the actual cost per ship yet," she said in an interview. "We're not talking about a custom build anymore. We're talking about existing designs ... and in our view that is likely to have an impact on diminishing all sorts of risks." There would be, however, some modifications to the design to suit unique Canadian requirements. ... Naval buffs will likely mourn the design decision.* (Brewster, 2016)

The attractiveness of such arguments early in an acquisition plays well into competitive evaluations and redesigns. When such redesigns play out in the fullness of unique requirements and new technological fit-outs (the '*shopping basket'* of systems), it means that the off-the-shelf schedule and cost savings can usually be characterised to some extent as both a fallacy and mirage. An excellent treatment of this fallacy is in the report '*Australian Senate Inquiry into Defence Procurement'* (Australian Senate, 2012, Chapters 2 & 12). There is probably a no better example of such fallacy being realised than Australia's Air Warfare Destroyer program, that took 15 years from requirements to the first ship's operational testing. So many years is much longer than the FFG-7 and ANZAC first-of-classes, and the ships cost three times the original estimates.

The global stagnation of Defence research and development, outside of a few critical areas in the U.S. and China, is apparent in reviews like Bitzinger (2016). Specific to maritime, Bitzinger (2016) covers the U.S. Navy DDG-1000 program and attempts at new destroyer and cruiser designs (DD-21 & CG-21). He cites Luttwak (2007) 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 (1986), 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".*

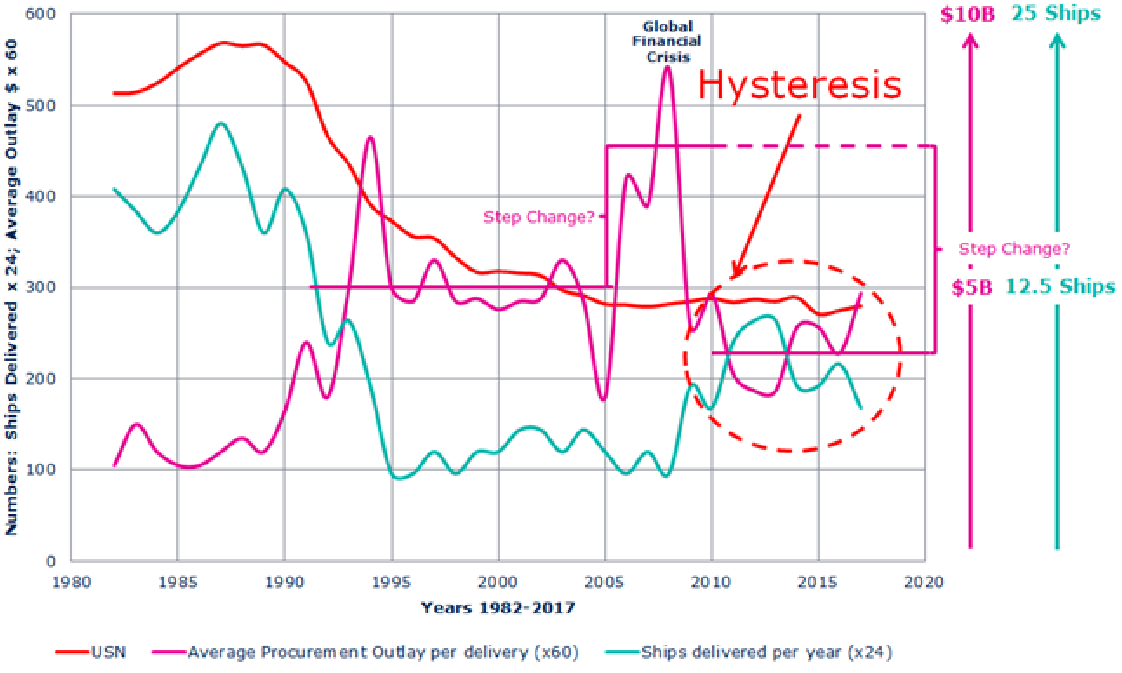
Kaldor (1986) herself states,

> *'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 (2007) 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*."

Pugh (2007) considered cost per unit size or cost per tonne (1000 kilograms) of Basic Mass Empty (BME) as a means of examining system/class behaviour. Reay Atkinson (2012) applied BME to hull build costs for UK T22 and T23 Frigates to compare system designs and build costs. The Batch 1 T22 had a mean BME in 1980, 83 per cent the mean cost of building a T23 in 1994; 63 per cent of a Batch 2 T22 and 67 per cent of a Batch 3 T22. Calculating DCI between the mean costs and (production) years, DCI for Batch 2 T22s was 8 per cent; Batch 3 T22s, 5 per cent; and T23s, 1.5 per cent. It could be concluded that the T23 was a re-design of the problem since it had a much-reduced DCI. This conclusion though overlooks the fact that the T23 optimised the same systems as a T22 (Batch 2-3) into a smaller hull than a Batch 3 T22. In other words, this was not a new '*conceptualisation*' of the design problem but an 'optimisation of the design space'. 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 (1994), systems coming "*offload*" show hysteresis, identified in the wide swings in BME costs of latter T23s (Reay Atkinson, 2012), and seemingly in *Average Procurement Outlay per Delivery* (about an average of about $4B) variations, amplified (60 times) in Figure 2.



Navy Force Structure and Shipbuilding Plans: Background and Issues for Congress, December 22, 2017

Figure 2: US Navy 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 U.S.). More demanded from even less to the point, potentially, of *reductio ad absurdum*; sweating assets and people at the expense of readiness and productivity.

Reviews illustrate that the recent Iraq and Afghanistan wars have been significant for designs in land forces and counter-insurgency or irregular warfare (Kiras, 2016; Reay Atkinson & Sharma, 2007) but not for air and naval platforms. These wars have led to almost no revolutionary design, or new Conceptual Design Spaces (CDS) (Reay Atkinson, 2012) in the air or naval platforms. This limited reconceptualization has been during a period of increasing indivisibility of information from the technological, and the social from the IT (Reay Atkinson et al., 2016). Such contrast suggests, as also confirmed by hysteresis in the system, that we are at a critical juncture when existing designs are no longer affordable, and it will be necessary to break out of the cost inflation trends as characterised by Pugh (1986, 2007) and Augustine (1997).

4. High-level Strategies

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

1. **Abstracting, conceptualising and creating new designs – new conceptual design spaces**. This design approach is advocated. The revolutionary designs of FFG-7 (and UK T42s and T22s) 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. (Riekhoff & Gongora, 2000)
2. **Reconceptualising and redesigning** existing classes and combinations/compositions of systems / capabilities / platforms. For example, the U.K. ship HMS OCEAN (L12) designed to commercial standards came in at the same mean unit cost of the Invincible Class carriers built 20 years earlier (Reay Atkinson, 2008).
3. **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.
4. **Spending much, much more** (power-law increases in budgets) to maintain/preserve existing (obsolescent) design and build capabilities, e.g. the T45, 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 T26 was chosen. However, by cost and BME, the Hunter Class remains a derivative of the FFG-7 and UK T42s.
5. **Stop and get off**, as the U.K. Royal Navy appears to have done:

> *Even if the T26 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 T22 and T23 Frigates). Instead of purchasing eight anti-submarine versions and five general purpose versions, the government is now committed to buying just eight ASW frigates.*[6] *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*. (Foreman, 2017)

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[6] Currently (2019 Foreman was writing in 2017] there are 31 Global Combat Ship variants under order, 8 for UK (T26), 9 for RAN (Hunter Class) and 15 for the Royal Canadian Navy (Canadian Surface Combatant Class)

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.

5. The Revolution That Was FFG-7

The FFG-7 class frigate was for the U.S. Navy 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 U.S. 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 U.S. Chief of Naval Operations, Admiral Elmo Zumwalt, a charismatic and visionary leader who insisted on new approaches to lingering challenges, especially those central to the then Cold War. FFG-7 was the quintessential low-mix and was heralded to demonstrate the mantra of Soviet Fleet Admiral Sergei Gorshkov who proclaimed, 'Better is the enemy of good enough.' FFG-7 was to be designed only to be good enough and to be "expendable tin cans". Faced with that intent, the FFG-7 designers embraced many unconventional and even revolutionary required characteristics, including:

- Two high capability anti-submarine warfare (ASW) helicopters, initially LAMPS-1[7] SH-2D Sea Sprite aircraft as an interim step while the Sea Hawk program was underway, and ultimately from the third flight of ships (the FY79 design baseline) included AN/SQR-19 TACTAS towed array sonar, more advanced EW and other C4I systems and two of the much more capable and heavier LAMPS-3 SH-60B Sea Hawk[8] aircraft and associated shipboard command and control equipment. These aircraft also provided over-the-horizon targetting for anti-ship cruise missiles.
- A Recovery Assist, Traverse and Securing (RAST) system based on the Canadian Beartrap system to enable operation of heavy aircraft from a relatively small deck up to Sea State 6. Canadian experience was acknowledged as pre-eminent in this respect.
- The ASW capability was further enhanced with LAMPS-3 from the third flight by the addition of AN/SQR-19 Tactical Towed Array Sonar System (TACTAS).
- An area, air-warfare defence missile system based on the Standard SM-1 missile operated from the proven Guided Missile Launcher System Mark 13 (GMLS Mk13). These were also used in the DDG-16 later ships of the U.S. Charles F Adams Class, as operated by the Australian and German navies, which was a significant factor in Australia's decision to join the FFG-7 acquisition programme.
- A smaller, lighter Guided Missile Fire Control System (Mark 92) based on the Dutch Signaal system with Americanisation of some components and human-machine interfaces by the Sperry group of companies and the addition of a continuous wave illuminator required for the target illumination for Standard missiles.
- The GMLS Mk13 also provided magazine and launching capability for the Harpoon Anti-ship cruise missile weapon in widespread use from a variety of launch platforms.
- A maximum number of 185 accommodation bunks for all members of the ship's force and of the fully embarked air detachment for two aircraft.

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[7] Light Aircraft Multi-Purpose System (LAMPS).

[8] On which the Australian Navy SH-70 was based.

- Ability to operate the embarked aircraft up to Sea State 6 with some limitations and up to Sea State 3 without any restrictions, day and night.
- Two LM2500 General Electric marinized gas turbines driving the main reduction gear applying revolutionary frictionless Synchronous Self-Shifting Clutches (Blake & Bellamy, 2016) to a single shaft with controllable pitch propeller. This design was proven in a land-based test site constructed at Philadelphia Naval Shipyard to be operated in three 21-day cruises by US Navy officers and enlisted personnel. The propulsion system LBTS was then dismantled as not requiring further development from the lead ship design, in contrast to the combat system land-based test site (LBTS) at Ronkonkoma, NY, which still had work to do on LAMPS-3, TACTAS and other subsystems such as Link 11 tactical data link.
- Ship-service electrical generation by two (later three) ship service diesel generators. The SSDG integration was not subjected to previous proof-of-concept and reliability, maintainability and availability (RMA) demonstration in an LBTS and was consequently a continuing source of reliability issues.
- ASW weapons to be delivered by aircraft primarily and to be ‘magazined’ in an above-waterline space protected by non-metallic armour made from Kevlar proprietary material.
- Close-in defence from anti-ship missiles by the mounting of a Phalanx Close-In Weapons System (CIWS) above the dual hangars.
- A secondary general-purpose gun system was also provided by a 76mm American built Mk 75 gun to the Oto Melara design; this was mounted amidships at the level of the hangar roof rather than the primary offensive weapon GMLS13 mounted on the forecastle. This location was questioned by gun armament advocates, especially the rigidity of the deck on which the gun was mounted.
- Aircraft hangar and lightweight torpedo and gun magazines located above the steel main-deck in aluminium alloy structure protected by Kevlar armour. The location of these magazines was queastioned by the United States Board of Inspection and Survey but subsequently accepted after successful full-scale penetration testing.
- A Combat System LBTS to provide an operational experience of the ship’s combat system design options (Asher, 1978).
- A then-novel requirement to integrate maintenance planning into the outset of the ship’s design and implement maintainability test and evaluation demonstrations during detailed design (Guido & Light, 1978).
- Other requirements were similarly revolutionary in many ways and gave rise to passionate questioning of all design features. In every case, the mantra of ‘Better is the enemy of good enough’, and ‘design-to-cost’ for long-run production overcame the traditionalists and other sceptics.
- Above all else, there was a unanimous acceptance that FFG-7 class ships were expendable in the interests of a convoy and amphibious group protection. This acceptance was the central theme of "design-to-cost" philosophy, e.g. a low mix of systems with a limited performance for low relative threat environments, but produced in an accelerated building program running concurrently in three shipyards.

The FFG-7 program management was run through three shipyards concurrently: Bath Iron Works in Bath, Maine as the lead shipyard for the design of ship modifications and builder of the lead ship; and Todd Shipbuilders in two yards – Seattle, Washington, and Long Beach, California. The building tempo was to be such that some eight ships would be delivered in each year

Notwithstanding, the U.S. Naval Sea Systems Command did appreciate that many of the features of the design were unproven in any stage of test and evaluation[9]. So they mandated the first-of-class [10] be constructed in a separate contract with Bath Iron Works. Also, there had to be more than a year between the delivery of the lead ship and the first of the '*follow-on ships*' to permit the test and evaluation process to provide the optimum influence on the overall design, while not being too far advanced of production (Asher, 1978). The value of the lessons learned in this deliberate pause is well documented by Stark and Stembel (1981), both of whom were intimately engaged in the FFG-7 program from its inception.

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 (Joiner & Atkinson, 2016).

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[11] and to a whole-ship shock test. The latter test comprised the deliberate detonation of large underwater explosive charges to verify the integrity of the hull design and the capability of ship systems to operate effectively after such an explosion. It should be noted that ASW weapons of the era included nuclear-tipped missiles that could be fired by friendly forces close to escorts such as FFG-7 class ships.

The importance of the land-based test sites in managing revolutionary designs is captured by Stark and Stembel (1981, p. 116) as follows, and is in stark contrast to the Australian experiences of the Collins Class Submarine a decade later (Joiner & Atkinson, 2016) and the Landing Helicopter Dock ships only a few years ago (ANAO, 2015):

> *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 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.* (Stark & Stembel, 1981)

All test and evaluation in the U.S., then and now, is based on an approved T&E Master Plan (TEMP). Accordingly, all developmental programs and other test issues were described in the FFG-7 TEMP along with the approaches to be used for all testing, the responsible agencies and the allocated resources budgets. The FFG-7 TEMP was the second author's responsibility and based on it, a quarterly report provided to Australia on all the same scope. The TEMP required Defense approval and had to be implemented as approved and updated on an annual basis. Quite separately, the U.S Congress exercised oversight of all Navy ship programs through the Board of Inspection and Survey who had to be satisfied independently.

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[9] Test and evaluation stages were: developmental, operational effectiveness and suitability for fleet employment, and production acceptance.

[10] Termed the 'lead ship' of the class.

[11] Conducted later in a ship of the Fiscal Year 1979 (FY79) design baseline when several significant changes were introduced including LAMPS-3.

6. 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-U.K. Falklands War in 1982, 35 years ago (Spellar, 2016).

This engagement reaffirmed the importance of maritime aircraft operations with stand-off missiles, the role of aircraft carriers and submarines generally. It contained lessons for naval engagement in the following areas:

- the timeliness of good intelligence, surveillance and reconnaissance (ISR) by both sides;
- long-range, remoted submarine sea control (in 1982, the U.K. had five SSN and one SSK in the South Atlantic);
- improved at-sea anti-aircraft and surface search radars (ship & airborne);
- anti-ship cruise missiles, notably Exocet, including the challenge for targeting of such long-range weapons;
- Short-Takeoff and Vertical Landing (STOVL) aircraft used by the U.K.;
- refuelling aircraft for land-based aircraft projection to sea, or buddy refuelling to extend the range or time-on-task – as applied by the Vulcan strategic bomber force;
- maritime patrol aircraft operations in reconnaissance for anti-ship strikes;
- resupply of aviation and ship service fuel, armaments and victuals at sea;
- electronic warfare in all its manifestation; and
- the ineffectiveness of anti-ship missile defences - lessons that seem always to need (re)-learning given the rate of advancement of these threats.
- The uncertainty of anti-submarine warfare capability. The possible presence of a single Argentinian conventional submarine gave rise to a significant expenditure of ASW assets by the UK.

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. These changes are likely to include (Morgan, 2019; Skinner & Morgan, 2017):

- substantially more computing power and associated analyst stations to process the significant data captured by AUVs;
- dedicated stations or interchangeable modules for docking, maintenance and storage of AUVs;
- specialist storage areas for fireproofing the high energy and long endurance batteries;
- additional communications systems to air-gap and underwater communications for the critical mission data from AUVs real-time; and
- additional monitoring in ship warfare centres to integrate AUV data into the decision-making for the ship's mission.

Speller (2016) covers the naval developments of sea-basing as a means for projection and its use by both Russia and the U.S. for such purposes. There are also elements of sea-basing in the Australian adaptation of a Spanish amphibious ship design (Canberra Class) for stabilisation in

South-East Asia and South-West Pacific; however, these are arguably minor re-purposing. Speller (2016, pp. 209-219) also predicts the continued development of maritime anti-access or area-denial weaponry as having the most significant effect in naval capabilities:

> *'... a combination of advanced systems and also the innovative use of cheaper low-technology capabilities might allow a wide range of potential adversaries to deny the seas to even the most powerful navy. ... 'China has concentrated on developing a range of joint capabilities, across all domains, that are designed to challenge US access and freedom of manoeuvre, aiming to keep US forces away from areas of Chinese interest and to threaten the viability of US bases ...'.*

Bitzinger (2016, p. 164) also points to Chinese research and development (R&D) as the most influential in Defense 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.*

Whether from this Chinese investment or because of it, or both, naval spending by the Asia Pacific region is exceeding Europe for the first time in 400 years (Till, 2016, p. 182). Raska (2016, p. 96) notes the particular attraction of submarines to South-East Asian countries; namely, that they can cost-effectively provide sea-denial without requiring an equivalent degree of sea control for sea power projection or trade protection. He explains:

> *'Stealth attributes of submarines provide strategic advantages over surface ships as the means for sea-based surveillance, particularly in the shallow coastal and littoral waters in the South China Sea and Java Sea.'*

With these forces at play, returning to the first precondition for revolution and using techniques outlined by Ross (2016) for identifying emerging military technologies, Table 2 is a listing of the critical emerging technologies in the Asia Pacific, and especially China, that ought to force and enable revolutionary warship design.

The existence in multiple countries of strategic surveillance satellites, long-range and reflective fixed radars (i.e. OTHR & HFSWR), and fixed or tethered sensing sonar arrays, make it much harder to project ships without detection. So such ships will need to be better defended, or considered expendable at an affordable cost (the essence of the FFG-7 designs). To this end, lighter-weight, high-powered radars are promising substantial reductions in the weight and height requirements of ship superstructures, at least to defend against high-speed threats. Unfortunately, high-speed threats are going into the hypersonic regime. At hypersonic speeds, the warning time of advanced strategic sensors like satellites will mostly be taken away as new missiles traverse every 1000 km in around nine minutes or less (Kemburi, 2016, p. 117). To defend from such high-speed threats require phenomenal sensor-fusion and signal-processing rates. One way to try to hide is active electronic rather than passive stealth and decoys such as NULKA. However, if the adversary has multiple sensors operating across many frequency bands, such stealth will be comparatively ephemeral to normal ship life.

The use of remote sensing with 360-degree display to a hardened command room is under development in submarines, enabling all sensor specialists and command elements to see and contribute, moving beyond the individual sensor operators on the deck of the *Star Trek* bridge. Such developments may finally offer ship control from networked command spaces rather than the highly vulnerable ship bridges of today, moreover moving those centres to more defensive positions.

Table 2: Critical Emerging Technologies effecting naval ship design, especially in Asia-Pacific

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

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 (Joiner & Tutty, 2018). Heinl (2016, p. 126 & p. 131) 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*.

The future naval warfare seen emerging in regions like South-East Asia is likely to be hybrid, for example, including piracy, terrorism & non-state actors with attacks on civil populations and infrastructure as well as military forces. Also, these forces are likely to use cyber warfare and sea mines because these are comparatively cheap, harder to attribute, and somewhat indiscriminate compared to conventional warfare. As such, future designs must be highly cyber-resilient and able to deploy mine countermeasures, such as Autonomous Underwater Vehicles (AUVs). Such advancement in technology could be a vital enabler of a nation's defence industry, such as in Singapore (Till & Supriyanto, 2018).

7. 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*' (Reay Atkinson et al., 2011). 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:

- *Glocal* (Global / Local) networked (internal & external) command spaces;
- enhanced defensive radars and ship defensive missiles to counter hypersonic threats;
- towed and fixed sonar arrays employed in concert with offboard sensors such as seabed arrays, sonobuoys and sea gliders;
- UUVs to assist with the detection and engagement of sub-surface threats and associated picture-complication processing;
- UAVs to augment the maritime patrol of crewed helicopters and aid in defensive awareness especially in congested waterways, and the associated processing within the command spaces;
- All this meaning that UUVs and UAVs may become the primary offensive sensor and effector systems and the mother ship, submarine or aircraft the operational support base.
- condensated interactive-networking with other ships and other allied assets to enable cooperative engagement and mutual defence; and,
- cybersecurity; including cyber-monitoring of all internal databus, external traffic; and, weak-signal RF probing close to land or other vessels, and the associated processing within the command centre (Joiner, 2017).

Modularising. Blake in a *New Model Navy* (Blake, 2014) 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; emphasizing the *agility* of crews to think through and solve problems tactically, and the *fidelity* of the system to enable *operational versatility* and *strategic adaptability* (Reay Atkinson et al., 2011). 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. The U.K. Navy is a case in point – but this also extends to the U.S. and Australian navies. Cuts in numbers of ships and crews (following the 2010 Strategic Defence and Security Review (SDSR)) led to predictable[12] over-swings in redundancies and premature retirements – leading to systemic gapping, notably amongst engineers. This cutting occurred to such an extent that in recent years the U.K. has been forced to recruit engineers and technicians from the U.S. Coast Guard and French Navy.

The VMS approach is based upon abstraction and conceptualisation of the problem. Such an approach is needed because critical underfunding of naval research since the 1990s appears to have resulted in unaffordable and ‘*uncrewable*’ surface warships. In contrast, investment and research have continued apace into submarines, merchant and unmanned vessels (maritime, land and air).

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[12] By, amongst others, the First Author during his time as SDSR strategic systems adviser to the British Naval Staff, 2009-2011.

The approach returns to earlier modular configurations; reaching back as far as 1694 and the synthesis of Admiralty with the City of London and the Bank of England – that underwrote and so capitalised the British Industrial Revolution (1760-1820) and Nelson's Navy (Reay Atkinson et al., 2011). Also, well-known examples dating back to 1970s: MEKO (Germany), Cellularity (UK), StanFlex (Denmark), and Ship Systems Engineering Standards (SSES) in the US Navy. The latter was initially incorporated in the early DDG 51 designs.

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 Table 3.

Table 3: Consolidated Conceptual Design Space Considerations

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.

Blake (2014) also stipulates as critical, the management of the flows of systems, crews and materiel between the Navy; its Auxiliary and Support elements[13] 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 (Reay Atkinson et al., 2011; Blake, 2014). VMS designs place sophistication (and adaptability) in the systems – rather than the hulls. From a crewing perspective, the model allows for crews to flow from one Flag to the other (even to fly-in; fly-out), and to specialise – for example in war-fighting (white ensign applications); logistics support (blue ensign) and trade and commerce (red ensign).

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.

To counter this Western-orthodoxy, the Soviet Union designed highly sophisticated, resilient, quantitative, and comparatively simple command doctrines and capabilities, such as Reflexive Control (Lefebvre & Lefebvre, 1984) (meaning that one reflected strategically before reacting tactically or operationally) and the AK-47. Similarly, the Pashtun doctrine-*d'résistance* is based on a simple maxim: '*You the West have your clocks; we have time!*' Taking the two concepts together, along with Stalin's maxim on quantity, the capacity to survive, loiter, take the hits, and afford the losses becomes a fundamental warfighting (as differentiated from peacekeeping) design consideration. Put another way, '*Capacity, Capability, Coherence, Consistency and Continuity*[14] *have a Quality and Quantity all of their Own*'(Reay Atkinson & Sharma, 2007). Such approaches are a stark contrast to the current trend in the Western nations for fewer more advanced platforms which may not be sustainable.

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:

> *In strategy, rank and position are two very different concepts. Ranking does not guarantee victory, but position does. Position is about the ability and agility to adapt and survive and defeat one's opponents. Rank is merely one element of one's position. The mismatch between rank and position is the ultimate strategic nightmare and distinguishes strategy from doctrine and operational art, where Strategy is influenced by wider Political, Social, and Economic considerations.* (Reay Atkinson & Goodman, 2008)

An obvious source of quantity in Western order-of-battle accountancy is the ready availability of oil rigs, bulk carriers and container ships, plus cruise ships for personnel transport. One of the lessons from the Falklands War was the innovative and expeditious manner in which '*Ships Taken up from Trade*' were used effectively; notwithstanding, their vulnerability and subsequent losses. But it should be stressed that VMS in its systems-of-systems approach, including for crewing, is recognised to move well beyond this application.

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[13] As provided by: U.S. Naval Ships using unarmed auxiliary support vessels owned by the U.S. Navy and operated in non-commissioned service by Military Sealift Command with a civilian crews; the U.K. Royal Fleet Auxiliary and; as suggested by Blake (2014), a new Australian auxiliary service. Additionally, in Australia, the Defence Industry has been declared to be a 'fundamental input to capability'.

[14] Attributed to Major General John Drewienkiewicz British Army (Rtd.) and the First Author, at an ARAG *Quesitio*, Jun 2006.

There is some evidence that this Western predilection for the few super-platforms could be eroding. For example, in the airpower debate in the U.S., U.K., Japan and Australia concerning the F35 Joint Strike Fighter (JSF) (U.S. DoD, 2016), the key to Western thinking is in the terminology often used of it "*being affordable*". In air combat, the initial loss of F35 aircraft may, through high-rate networking, disclose the enemy's intentions and even precious electronic warfare codes entirely. Such disclosure can enable a quick, almost swarm-like collective response. Of course, there are some significant downsides from the F35 analogy. First, any networking on such a continuous and annealing way increases the cyber-attack surface and unless designed for cyber-resilience may increase cyber vulnerability and reliance on cybersecurity defensive measures. Second, the theory is hugely untested in air warfare, and with the persistence of Western nations, could be considered as the key to whether, or how long, the West remains omnipotent.

The air example illustrates a compromise for future ship design, where singular ships are less defendable but synergistically-networked so the fleet can collectively be more recoverable and thus dangerous. This compromise returns the argument to scale, scaling, networking and political, economic, and military affordability. The 1970s revolution was to differentiate the platform (essentially energy supplies/propulsion, the hull and hotel services); from capability. This approach probably went too far, as performance-managed accountancy regimes took the platform as being synonymous with the '*ship and crew*' to cut crew and ship numbers, accordingly.

Furthermore, capability drove strategy and designs: capability-driven policies allow the enemy to harness and so 'fix' one's capabilities to their advantage. It potentially confuses weapons and capabilities with political objectives. It can lead one to define one's enemies in simplistic terms of their capabilities rather than the more complex conditions of their strategy' (Reay Atkinson & Goodman, 2008).

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.

Thus, the commitment by the Australian Government towards a continuous Naval shipbuilding program is necessary to allow for cost-effective production, batch builds and reduction of associated risks. Such a commitment also needs to be based on recapitalising surface fleets, which will take political and economic will along with new financial designs, beyond existing models.

For example, Western Navies could more drastically apply system-modularisation (perhaps through "Intermodal Containerization") and enforce not simply the division between platform and capability, but the intermodal interactions between platform and content. This perspective change would require Navies to look beyond current platform-orthodoxies and consider applying perfectly acceptable merchant ship designs (where investment has been maintained) – at scale and numbers – to fit system-capabilities better.

"Versatile Modularisation", which is a form of agile adaptation, therefore becomes key (Reay Atkinson et al., 2011). The first Aircraft Carrier, HMS ARK ROYAL (II), was laid down in 1914 as a freighter, designed for the coal-grain trade in the Black Sea. More recently, the U.K. ship 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:

1. Ask first, '*what would we be doing, if we were at war – and, if not, why not?*';
2. Adopt the *Cult of the Imperfect*[15] – 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*'. Remember what Admiral Gorshkov said '*Better is the enemy of good enough.'*, with parallels to Voltaire of "not letting the perfect becoke the enemy of the good'.
3. Enable compositions for '*crewing the ship (and its unmanned vehicles that it operates and sustains); rather than shipping the crew*';
4. Scale capability-networks for '*fitting the kit; rather than kitting the fit*'.

8. Conclusions

A new conceptualization 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 (F313), following a collision in a Norwegian Fiord due (it is claimed) to a fundamental mismatch with the crewing current frigate designs (Blake, 2019). Addressing the political, economic and military affordability of ships and potential losses is needed to shift the efficacy of Naval surface warfare.

Naval capability needs to be based on investment programmes that restore industrial co-adaptive advantage, at scale, so they enable highly productive, competitive commercial ship-building yards. In other words, posturing as if countries are at war. There are seven main sub-conclusions to this research:

1. Generally, there appear to be the precepts of a revolution in warship design underway marking the chaotic state at the end of the *Information Age*.
2. While many contemporary designs add intelligent, new software-intensive, deployable systems, scaling and composing the size of future fleets through versatile intermodalisation becomes crucial, as a distributed and networked force is more defendable. In peer-warfare (but also non-peer peacekeeping operations), numbers do matter.
3. Rescaling fleets and affordability are serious design challenges as befits the word revolutionary, but the FFG-7 programme shows that such challenges can be met
4. Some compromise must occur soon in ship design. Singular ships are less defendable, but when fleets are synergistically scaled and composed can be much more dangerous.
5. Such a revolution requires Navies to commit to land-based test sites that precede ship build and manage system threats and obsolescence through-life. Such sites are particularly crucial to revolutionary design since they verify and validate informed decision-making based on an iterative test evaluation and remove the illusionary and ephemeral promise of "*off-the-shelf*".
6. The looming increase of trusted autonomous systems in the form of unmanned autonomous and remotely-operated vehicles must be addressed. These devices are likely to become the primary first line of conflict rather than ancillaries to manned warfare. This change in warfare, in turn, is expected to place new and essential requirements on warships to deploy, operate and sustain many such unmanned vehicles.
7. Above all else, any such revolution must address the entire spectrum of maritime activity available to support warships. For example, the use of oil rigs and undersea cables, sensors and vehicles, take-up of merchant ships such as bulk freighters for rapid conversion for military use as air vehicle bases and so on. Innovation ahead of crises is critical.

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[15] Sir Robert Alexander Watson-Watt, KCB, FRS, FRAeS (13 April 1892 – 5 December 1973), pioneer of British WWII Radars.

This research has illustrated there are valuable lessons to be taken from the FFG-7 program at the start of the *Information Age*, and these can be applied to warship design now at the beginning of what could be considered the *Synthetical Age*, in which warship design becomes a holistic process embodying strategic capability, information dominance and the realistic appreciation of lethal effects producing combat losses.

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