CAPABILITY VERSUS AVAILABILITY IN SUBMARINE DESIGN?

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SUMMARY

Capability and Availability are seen as terms adopted to encapsulate major features required in designing a new major warship, such as a submarine. With these terms it is worth considering what they mean when it comes to designing such complex naval vessels. This paper firstly considers both of these terms in turn and questions whether capability is often too narrowly defined and, aside from affordability issues, which are clearly crucial in designing any complex system to meet a set of capabilities, capability could be seen to be all embracing in regard to the set of qualities desired for a new class of vessels. If this is so, then "capability" ought to cover availability among other whole boat performance characteristics.

Turning to availability, from a design stance it is considered this has been something of a Cinderella topic when scrutinising discussions on submarine design in the open literature. Thus, there follows a brief review of some key published sources, including those presented at the RINA submarine conferences, which started with the RINA 1983 International Submarine Symposium. This leads to consideration as to why availability seems to be addressed relatively late in the traditional submarine design process, such that any drop off in a class of submarines, in regard to that force's expected availability, might not be revealed until such a new squadron of vessels is fully in-service. This then raises the question as to how the process of designing such complex vessels might be better focused, in early stage design, to address the issue of availability. Without better consideration of fleet wide availability, the other operational capabilities sought in an affordable new design are unlikely to be effectively deployed at sea to a cost-effective level of availability. This new focus for submarine designers, is seen to be best addressed from the start by adopting an architecturally based "ship synthesis" approach and to be assessed at a fleet or class level.

1. INTRODUCTION – CAPABILITY VERSUS AVAILABILITY - REALLY?

"…the readiness is all." William Shakespeare (HAMLET)

Capability is an oft used term in the early consideration of a new naval vessel. Its usage can be traced back to US Defense Department's practice post-WWII (Hitchens, 1986), which was driven by a desire to change the emphasis in evolving new military equipment, from performance focused specific needs, to emphasise instead the military capability that the new equipment is intended to meet. Whether this was a good change in procurement practice for naval vessel acquisition is open to question, as this author has recently debated to a USA audience (see Andrews, 2022) when addressing a systems approach applied to naval ship design.

If we consider "capability", does it just mean the combat system part of the whole warship? This is often how it is seen by naval combat engineers, and even the more generally focused systems engineers, the latter of whom ought to know better (see again Andrews (2022) demolition of such engineers' usage, summarised in the next section, of the terms platform and payload). If "capability' is intended to denote what the new warship provides to the fleet, leaving aside all that "Float", Move" and "Infrastructure" provide to the "Fight" (combat system) aspects of capability (see Andrews et al, 1996 for definitions of the above terms defining a warship's functions), then capability must also include, for example "stealth", which itself permeates through out a submarine design in a "transversal" manner. But if submarine mobility (i.e. Move) is taken to include the need to dive to a specific depth and all that is implied by "safety considerations", for such a safety sensitive vehicle as a fast deep diving submarine, then there can be little in submarine design that is not a necessary component of capability. This then leaves little regarding the performance of a new design that can be sensibly omitted from "capability" beyond, perhaps, "affordability". Given this last aspect addresses the price to be paid for a set of capabilities, it can be seen as the other prime design consideration, alongside performance/capability, in achieving a "cost-effective" solution? So, should such a wide consideration of capability, balanced by affordability, not also include availability or, as we shall see, "fleet readiness profile"?

It is worth considering why availability has been something of a Cinderella consideration in submarine design (and indeed warship design in general) and, by the implication of this conference's title, whether it should be seen as separate from capability, which this paper's opening paragraphs have argued should not be narrowly (combat system) defined but include all design aspects, including availability, but perhaps not affordability, when adopting a cost-effective acquisition stance?

In two recent papers to previous submarine conferences (Andrews 2017, 2021), the author has argued that availability is a significant capability to be sought in submarine design, alongside all the many other interacting capabilities (well beyond combat system features) that the submarine designer seeks to provide in any new submarine design. Thus, in the 2017 paper outlining the unique set of issues associated with achieving a balanced submarine design, integrated logistic support (ILS) considerations were said to be a significant issue to address early in submarine design, where availability ought to have been taken to be included among the ILS suite of issues. And when the set of typical design choices (which need to be coupled with meeting the demanding physics involved in operating a submarine at speed and depth) are sequentially listed in the second (2021) paper, the order in which they are discussed is clearly qualified by the fact that these choices really are all interrelated and must be considered as a whole. One of the clear considerations (capabilities?) is delivery of a high level of availability – and that means, as will be seen below, the availability achieved should be that for the whole fleet of submarines that a navy wishes to deploy.

Availability should be easy to define: most engineers are introduced to the triumvirate of ARM (Availability, Reliability and Maintainability) early in their education and then get on with the things that interest them. A recent major focus on Availability in submarines, to which we will return later, highlighted the lack of precisely that aspect when the Collins Class SSKs were introduced into service in the Australian Navy. Fortuitously, the Commonwealth of Australia has published several detailed reports on the work of the team led by John Coles, into this severe drop-off. The second Coles Report (Coles, 2012) adopts the term "Sustainability" rather than availability but spells out, for the six Collins Class vessels, the availability of that fleet in terms of Material Ready Days (MRD) benchmarked to an "Average performance of international programs" using that term scored at 1.0 against the RAN achievement of only 50%. This, without the (classified) actual MRDs, is a stark comparison and puts in poor value for money (VFM) terms any focus on "capability" without spelling out what Coles identifies as "a readiness and availability requirement for the class".

Thus, the current paper next considers how (if at all) the classic texts on submarine design, including many in previous RINA submarine conferences, since the first in 1983, have addressed availability and, importantly, in the design phases, how an acceptable "capability" in that regard might be achieved. Section 3 considers, from perusal of many of the specialist texts on submarine design, why, given its importance, availability would seem to be relatively rarely addressed in the vital early design stages. Section 4 looks at different strategies for designing and acquiring submarine and how they place availability in context. Section 5 before the concluding remarks, considers if and how in the overall submarine design process, the issue of submarine readiness and availability can be better addressed by being regarded as a distinct focus within the overall capability sought. In particular, this is seen as changing the mind set to the sustainability of a given fleet of submarines, rather than being focused on an individual submarine's capability.

2. HISTORIC CONSIDERATION OF AVAILABILITY IN SUBMARINE DESIGN

In considering how availability has been addressed in submarine design practice, one could start with the classic textbook produced by Burcher & Rydill (1994) and which is still the basis for the only open post-Masters level short course in submarine design. This has been run at UCL since the early 1970s (www.ucl.ac.uk/mechanical-engineering/study/other-programmes/submarine-design-acquistion-course). With their focus on early-stage design, the term "availability" does not even figure in the book's Index, 'though there is throughout the book a strong emphasis on safety, which is a significant driving concern in maintaining submarine availability.

Early papers on modern submarine design in the RINA submarine conferences, from the first in 1983, have also focused largely on direct design issues, with only a few papers addressing thought life support in general and even fewer directly considering availability.

At the 1983 RINA Submarine Symposium, Daniel's scene setting paper "Considerations influencing Submarine Design", from a major player in UK early SSN/SSBN design programmes prior to his being in charge of the, then, nationalised UK warship shipbuilders, gives an overview of the main submarine design issues. Daniel's (1983) exposition culminates with the introduction of the UK SWIFTSURE Class SSNs. With this class, the nuclear attack submarine attained a design maturity, as has previously been outlined by the current author in his papers to recent RINA submarine conferences mentioned in the Introduction (Andrews, 2017, 2021). Apart from additional sections, beyond the usual naval architectural submarine topics, where Daniel discussed the sensitive issues of Survivability and Noise, he gives a submarine designer's view of machinery and life support. Thus, Daniel overlooked the whole set of issues concerning through life support, including the need for an extensive investment in nuclear power related shore support facilities as part of maintaining the availability of the fleet as a whole. This was common in other "design focused' early submarine conference papers, as is summarised in the brief reviews of a range of seminal papers below.

An even earlier review paper in the SNAME Transactions (Arentzen & Mandel, 1960) provided a very comprehensive (over 50 pages) state of the art on the "Naval Architectural Aspects of Submarine Design" from a US Navy perspective. In the paper and its extensive written discussion, the naval architectural aspects were (interestingly) limited to what could be considered the "classical" view of naval architecture in "ship design" by focusing on the S^4 ship design aspects of Stability, Speed, Strength, and Seakeeping (see Brown & Andrews, 1980). It should be noticed that the 5^{th} "ship design" aspect, that of Style, was not explicitly addressed, perhaps being seen as more of a term to cover broader design issues than the other four traditional ship design concerns. Thus, of the wider issues relevant to the submarine design process, in part addressed in Burcher & Rydill's textbook (1994), Arentzen and Mandel just deal with build cost, such that through life supportability, and hence availability, are implicitly not seen as directly part of the naval architecture of submarines.

An excellent detailed presentation of the UK design of a modern SSK (now operated by the RCN) was presented in the RINA Transactions by Wrobel (1985). It provides an exposition on that specific design, and when it comes to issues associated with through life support and availability, Wrobel draws attention to the incorporation of a "Dutch Breech" in the pressure hull to facilitate removal of the main diesel engines. This was a significant design investment to improve availability. A similar feature in the UK Trident VANGUARD Class, taken from the USN OHIO SSBNs, was to incorporate two Logistics and Escape Towers (LETs), each giving a 6 foot diameter opening in the pressure hull with appropriate in-board removal routes to facilitate the removal of much of the boat's equipment.

A good review by Prins and Everard (in 1996 RINA Submarine conference) presented a Dutch/VSEL (now BAES Barrow) perspective of 15 conventional submarine designs, each with a cutaway profile focused on propulsion features. An interesting view (Fig 4) of "design iterations" covers ownership and support issues, however the term performance is not seen as needing to address availability. However, Prins and Everard do cover reliability and redundancy, and both aspects could be said to contribute to availability but here they only consider both issues with respect to Survivability and in considering the implementation of several AIP options, rather than its role regarding the whole set of submarine design choices (Andrews, 2021).

Prins and Everard, (1996) like many presenters, use the term "platform" and so it is considered worth, for this specific submarine audience, to comment as to why this is so inappropriate for something as complex as a military submarine and, specifically, nuclear powered attack SSNs. It would seem this usage originated with naval combat engineers (and their close engineering colleagues, systems engineers), who have gone seriously wrong and practiced a poor systems approach by applying the term 'platform' to naval vessels. In contrast certain software design engineers devised the term systems architecture, and in doing so say that they have followed the practice of naval architects (Maier, 1998)), and thus the appropriateness of systems architecture compared with 'classical' systems engineering has been outlined for complex vessels by Andrews (2022). While a naval combatant (or a submarine) can provide a physical platform for complex vehicles, like helicopters and UUVs, it is wrong to use the term "Platform" to describe a naval vessel as such. It is a whole system of systems and the further split into 'payload' and 'platform' (i.e. combat system and the 'rest of the ship') is a very bad design and acquisition mind-set. It implies the former is good and must be maximised at the expense of the latter.

So, the so-called "platform half" of 'the platform' (itself a tautological nonsense) provides flotation/survivability and mobility, both of essential military worth. That 'ship half' (which it may be in cost of acquisition terms, but is far more than 50% in terms of whole boat space demand, that directly drives ship and boat size) also provides the infrastructure for the personnel (who are largely 'fighting' the vessel) as well as the supporting ship services (such as electrics and chilled water) without which the combat system elements could not function at all. All of which shows the utter nonsense of the "two halves", which amounts to not seeing the warship as a whole system of systems. Thus, all the interdependent functions contribute to the vessel's capability, which means there is no unnecessary 'platform overhead' to be minimised. This typical combat system and procurement policy mind-set has led to false justifications to reduce whole ship capabilities in vital features, such as those contributing to sustainability, supportability, adaptability, robustness and mission flexibility, with through life cost consequences well beyond individual designs. The example of the "margin-less and short life" Type 23 Frigate programme is discussed in Section 4 of Andrews (2018) and the consequence of the Type 42 destroyers 'platform' inadequacies in the Falklands Campaign have been outlined in some detail in a forensic discussion of the losses in that campaign in Andrews (2022).

A paper addressing the RN nuclear submarine "design challenge" was published in *Nuclear Energy* by a former DG Submarines (Betts, 1999). Betts rightly commences with the design process, seeing it as a process unique to nuclear submarines, with four clear categories needed in a "draft" set of requirements: role; operating environment; performance; and, directly, availability, before summarising an extensive concept design. Betts also reflects on the introduction of the UK Ministry of Defence design tool SUBCON (Andrews et al.,1996) as a graphically based CAD tool and then its subsequent object-oriented version in QinetiQ's Paramarine design suite (www.paramarine.qinetiq.com). This application of the UCL Design Building Block approach (Andrews & Pawling, 2003) has enabled early design consideration of accessibility for (among other aspects) maintenance envelops, in the congested layout of a submarine, to ease maintainability and directly contribute to ensuring adequate availability of a new class of vessels. Furthermore, Betts then addressed more than the usual naval architectural considerations in submarine design by including topics such as noise, safety and auxiliary systems, but omitted to emphasise availability issues. The section on construction mentions the, then, GEC Marconi (now BAES Barrow) intent to use both CADCAM and a modular build process, both of which ought to have emphasised too their joint advantage in exploiting the availability implications, but, yet again, this was not explicitly discussed.

In the same year in a keynote paper to the RINA submarine conference, Fuller (1996) stated in his paper's title that the "essentials of the submarine are: To dive; To move; To live and To survive". In calling for a "holistic" design approach, Fuller reviewed 126 RINA submarine conference papers to that date and while the largest number were those on design and powering/AIP, there were less than ten each on structures, life support, resistance & propulsion and on survival. So again, availability was noticeable by its absence. In the paper's concluding section, that author saw (post-Cold War) that, for the immediate future, (evolutionary) designs are likely to be no more than stop gaps "until *the future submarine* requirement *has been* articulated". He then listed six likely drivers of new design concepts, with the fifth being "low maintenance materials and equipments, easy hull access", which could be seen as a partial recognition of the true importance of availability in modern submarine design?

In that same conference Tasker and Wilcox (1999) (from Marconi Naval Systems (soon to be BAES, Submarines) and UK MoD, respectively) presented the RN ASTUTE Class SSN design, following its March 1997 prime contract placement, with (what proved to be wholly optimistic) first of class (FoC) in-service date in 2005. From the current conference's perspective, interestingly, that paper talked in outlining its design process of: "concurrent engineering"; a modular construction; and identified, in a final "Realisation" subsection, "Design for Support". This started with stating the "Astute Class is the first RN submarine designed for support from the outset", by emphasising the provision of "the first 8 boat years support within the contract price". Whether (after considerable time and cost renegotiation in the subsequent Astute contracts) even this limited through life support has been reflected in the "guaranteed" availability of the whole class, is clearly an open question. It is likely to remain so, at least in the public domain, until well beyond the current decade, when it might then be seen as just an historic issue with, hopefully, some lessons on enhancing availability being useful to future submarine programmes.

The first of several more recent American perspectives than the 1960 one above, was presented by Sullivan and Tibbitts in the naval submarine chapter of the SNAME two volumed "*Ship Design and Construction*" (Lamb, 2004). This comprehensive review starts with Missions; then submarine history; design drivers; features unique to submarines; and "ship" characteristics. So at least in talking of "Producibility Concerns and Modular Construction" in that last section, there was an opportunity to cover availability of a whole class of vessels but, as has been seen pretty consistently in this section of the paper, a focus on the many challenges in submarine design has all too often been at the level of an individual submarine's performance and production cost, rather than the proper focus on a navy's submarine force's "capability". Thus, it can be concluded from this brief review that Availability (like most ILS issues) needs to be far better considered in the "design fight", which has been largely between just capability (often combat system focused) and again, largely, Initial Cost of the individual FoC design rather than the fleet resource that a whole new class of submarines actually provides the modern navy.

3. WHY IS AVAILABILITY CONSIDERED SO LATE IN SUBMARINE DESIGN?

In order to answer the obvious question as to why availability has been largely disregarded by most publications on submarine design and seen (if at all) to be considered relatively late in the design process, along with the rest of ILS, it is instructive to explore those few papers, mainly presented at more recent submarine conferences, that have considered submarine design for support and whether they have specifically addressed availability.

A COLLINS Class paper from ASC and Saab Dynamics authors (Smith & Stenholm, 1996) addressed the system management (unfortunately using the term 'Platform Management', thus perpetuating that misnomer) when focusing on a higher degree of automation for, specifically, the manoeuvring and propulsion control needs as part of an integrated “Ships Control System” (SCS). It was realised that redundancy (always vital for all submarine systems with significant safety implications) needed to be addressed in the design of any SCS. In searching for higher levels of automation, the authors discussed “cost of the asset and its availability” and then pointedly stated direct crew costs (already a driver on levels of automation) “are usually small relative to costs associated with having a boat tied up alongside”, yet go on to say this is ”not readily assessed when suppliers are tending for a new design” and ”a boat alongside *(inoperable or deployable?)* is the province of the politician”, which seems bizarre as it is only the project manager and his engineering team that could actually address this. This degree of abrogation by part of the engineering design team seems pretty stark, and highly questionable, even before in this specific design, in-service subsequent revealed the failure to address the Collins Class availability. The last three sections of the paper addressed “Economic Considerations”; Operability”; and “Training” with, again, a focus on single boat’s operability, rather than emphasising fleet availability, which would have been more relevant once several boats were in service and fleet availability was found to be severely deficient and poor Value for Money (VFM). (See the Coles Report (2012) for further consideration, discussed below.)

Nicod (2011) of DCNS provided to the 2011 RINA conference, a technically well-argued focus on maintenance issues in early (“Basic”) submarine design with a refreshingly more ILS focused consideration, starting in ESD. Actual major design alternatives were explored for their performance versus cost for different “maintenance concepts”. It is good to see at ESD the proposal that specific decisions could be made affecting availability, such as H.P. bottles maintenance and whether they are to be located outside or inside the pressure hull. Such decisions can have profound implications for the vessel’s size and build cost versus ease of TL maintenance. This example is taken by the current author as a justification for adopting the UCL Design Building Block (DBB) approach to ship and submarine design synthesis (Andrews, 2018), however, one might argue with the performance index chosen by Nicod and the life cycle costing logic, using a “rhythm of maintenance”. The latter was used to show the effect of whole boat configurational choices, which is to be applauded, ‘though Coles investigation (2012) suggests that consideration at a fleet/class level would be a better metric of fleet ownership.

After two SSK focused papers, just discussed, Smith (2011) from Babcock International addressed an ILS driven approach to submarine design for, specifically, the UK Successor SSBN programme, where availability for naval forces deployment is transformed from direct naval warfare issues. Thus, the UK national priority to have a SSBN at sea at all times plus a standby SSBN available to go to sea at short notice, results in the traditional ARM consideration being up rated to “Mission Availability”. Smith’s design-for-support approach lists consideration of seven physical locations, for submarine support facilities: equipment onboard; at baseport; at other support facilities; and at the original equipment manufacturers. However, he commences with the issue of provision of adequate onboard access, defined as “the ability to access the system/equipment to carry out planned and unplanned support activities”. This, I would contend, is further support for an architectural/’inside-out’ (i.e. DBB (Andrews & Pawling, 2003)) initial synthesis approach to better achieve a support driven design with sufficiently practical access spaces being incorporated in the design before the submarine overall balance is fixed.

In 2012 a team led by John Coles, former Chief Executive of the UK Warship Support Agency, which had been the largest UK government agency by spend and, who was also Head of the RCNC, produced the second of several reports on “Sustaining Australia’s Strategic Collins Class Submarine Capability” (Coles, 2012). Despite using the first of this conference’s two key terms, that report addressed the second, namely Availability. The overall study by Coles’ team was provoked by the evidence that the availability of the Collins Class SSK fleet was well below comparable SSK fleets. In his Introduction Coles lists his key observations, which included:

- “current level of availability..*is* ...poor” both absolutely and relatively;
- practically, for a six submarine fleet, three should “always be available” “and sometimes four” (see Figure 1);
- “logistics support arrangements” did not support that level of availability;
- “Reliability has been the poor relation” and that is “not simply a case of buying more spares…”.

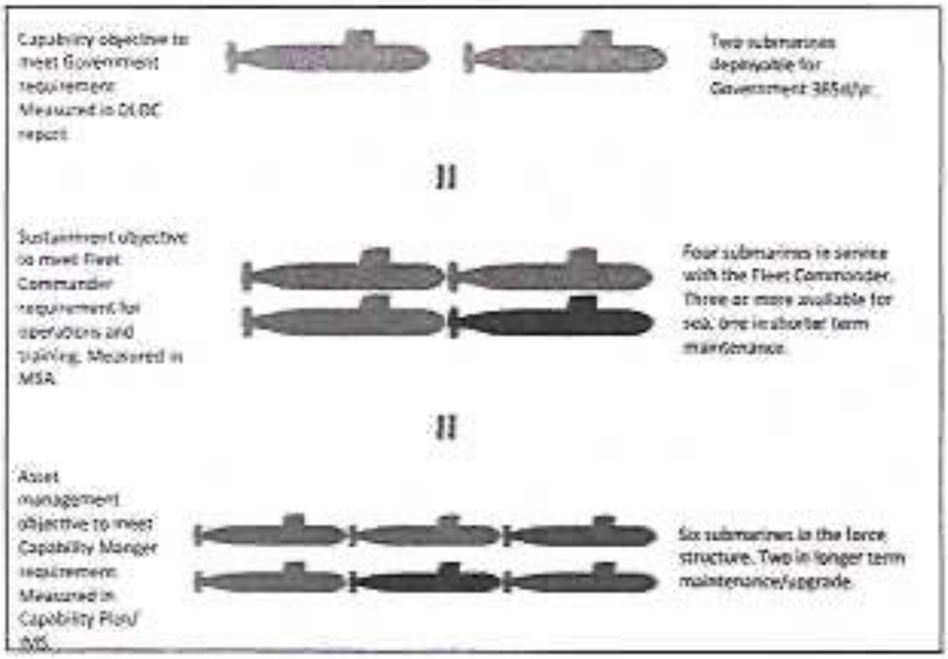

Figure 1. An example of a clear operational objective (Coles, 2012*)*

The details in the Coles report justified the above criticism with five main issues identified and 25 Recommendations spelt out, if that fleet were to get to the level of 3, or even 4, boats availability. Most of Coles' recommendations were primarily, cultural and then organisational, fundamentally requiring the government and navy to be an intelligent customer for sustainability to achieve a level of availability for this fleet comparable to that of the best submarine fleets worldwide. From this report, which proscribed a retrospective remedial programme, it should be possible to read across to a future project for a fleet of SSKs (or even SSNs) what needs to be done to substantially enhance the acquisition programme's focus on fleet availability.

In the same time frame as the Coles' Study, a more direct US Navy "Design for Sustainment (DfS)" approach for the OHIO Replacement (OR) SSBN Class was published in the USA (Baker et al., 2015). It gave a very direct intent for this major programme to enhance the availability of the new fleet arising from a reduction in class size from 14 OHIO SSBNs to 12 OHIO Replacements, while still providing the same level of strategic deterrence. Thus, a Sustainment Engineering organisation has been set up at the shipyard (Electric Boat Corporation, Groton, CT) to design for the OR life cycle, and the paper outlined the manner in which this is being done. Baker et al. stated the SSBN design "has been directly and substantially improved" in regard to "material availability" through life and this is due to these DfS improvements being accomplished early enough. It would be interesting to see what this has meant in submarine design terms, but this is unlikely to be revealed for such sensitive vessels.

From the review of the above, more availability focused, publications, it is concluded its importance is becoming recognised and that the issue has to be addressed at a fleet/class level and, also, this has to be done right from the initial sizing/synthesis of a submarine design project. Furthermore, as Coles concludes, even for a class of SSKs, that they are expensive to maintain (even relative to surface warships) but the issue is not just one of providing extra money both in build, facilities and support resources (including crewing levels). More important is a Very High Level of national commitment and one can conclude, even for conventional submarines and yet more so for SSN/SSBN (see Macdonald & Nicholl (2022) discussed below), that tackling availability adequately imposes the need to manage a submarine design wholistically. This author considers this to mean that the "fuzzy" side of naval ship design and acquisition needs to be more directly addressed as part of managing the production of such complex designs (see Andrews, 2022), so the next section considers recent suggestions as to how this more holistic stance might be better achieved as part of a better focus on availability for a fleet of submarines.

4. MANAGING SUBMARINE DESIGN WHOLISTICALLY TO BETTER EMPHASISE AVAILABILITY

Systems engineering (S.E.) has (since the success of the Polaris acquisition programmes in the US and UK navies) been seen as synonymous with (naval) ship design, at least by some while being questioned by others (Rydill, 1966; van Griethuysen, 2000; Andrews, 2011). At the 2008 RINA Submarine conference, Gordon MacDonald of BMT, Australia, in talking of naval architects, systems engineering and submarines, showed (at his Figure 1) the "fundamental inputs to Capability" with support and facilities flagged up but not availability directly (MacDonald, 2008). The classic S.E. elements in the ubiquitous "Vee" diagram, as shown by MacDonald's illustration, lack feedback and the insight of the seminal Royal Academy of Engineering's publication (Elliott & Deasley, 2007). Their figure on page 16 of their report, which is reproduced below as Figure 1, shows in the first bubble, to obtain capability, requires cost, time scale and risk, all derivable only from "possible solutions". Furthermore, those most plausible solutions ought to explore "fleet availability" if they are to be consistent with this paper's message. MacDonald's paper goes on to compare the systems engineer at "the centre" as "key integrator" (for general projects see MacDonald's Figure 6) with the naval architect as the **ship** design key integrator (see MacDonald's Figure 7). One could use that author's "Maritime Systems Engineer" term but this author would rather name the naval architect as "(ship) systems architect" (Andrews, 2016). Either way, a holistic Through Life (TL) approach to ship design and ownership that addresses availability is clearly a significant part of the initial ship designer's (naval architect's) responsibility, even if this S.E example failed to address it directly, which is reinforced by the "Vee diagram" ending at acceptance, with a brief nod to "sustainability" and eventual disposal at end of life.

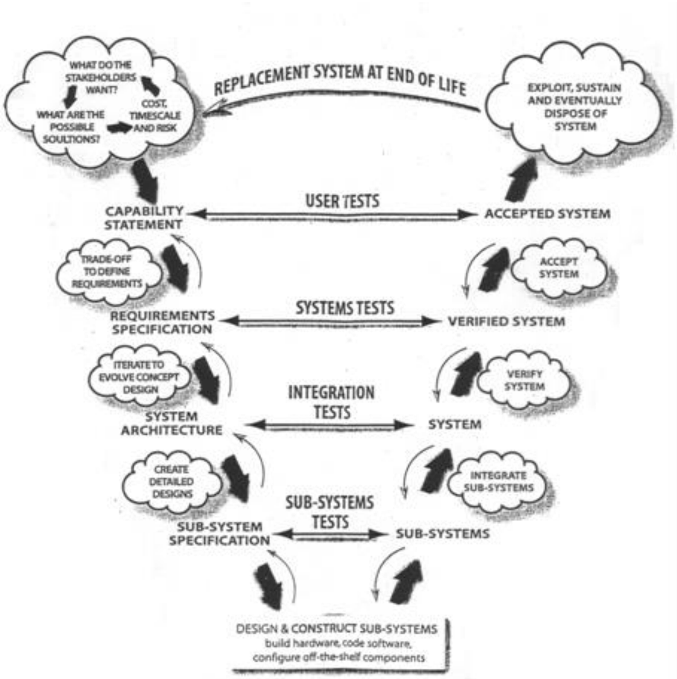

Figure 2. RAEng Vee Diagram for Complex Systems (Elliott & Deasley, 2007)

Another approach to naval ship design (with a SSK focus) could be said to have been presented by using Operational Analysis (OA) to derive the desired submarine capability for the Swedish Navy (Nordin, 2014). While Nordin purports to be able to make all the "design decision" using OA scenarios, the current author was able to question this regarding the classic omission in a SE approach when it comes to resorting to the old design chestnut "form follows function". As argued in Andrews (2018), this statement, due to the 19th Century architect Sullivan, is false (and has been recognised by architects, for many decades, to be a mere style choice but still accepted by most engineers). As Nordin shows in his Figure 21, Input Needs/Initial Requirements can only result from solution(s) (as in Figure 1) to be tested by the **designer** (as part of Requirement Elucidation) through the designer making choices on the Style of each individual solution when to synthesising new designs (Andrews, 2018)). Thus, Nordin designates "Set Design parameters and philosophy (Style)" (not to be confused with Set-Based

Design - see next paragraph) to then size (using volume and weight distribution) and test for balance (for submarines this fundamentally consists of: weight/buoyancy; resistance/powering; vertical and longitudinal moments balance (Andrews, 2017)). With this (non-SE) insight, one then looks for recognition of a "fleet design objective" to address "availability" (given the Swedish Navy's need for several boats to accomplish their specific operational role in the Baltic Sea). As with the previous Australian SE approach, availability/sustainability of a submarine fleet in Coles (2012) terms, could have been incorporated in this OA approach but once again seems to have been omitted from a holistic, but single boat, design consideration.

Work on two current US Navy nuclear submarine programmes was presented to the 2017 RINA conference from NAVSEA's controlling approach. The first by Daley et al. (2017) looked at ESD uncertainty and reducing risk, for the OHIO Replacement (SSBN) Class, while the second by Parker et al. (2017) considered the application of Set-Based Design when applied to ESD of the new submarine attack class (SSNX). The OR Class has already been discussed from a sustainability stance in the last section, but the Daley et al. paper is a more direct naval architecture focused exposition dealing in some detail with the choice of hull dimensions and the issue of weight/stability margins. The OR SSBN paper's main issues are preceded by a brief coverage of "Arrangements" that specifically mentions "sustainability requirements" but without referencing Baker et al. (2015) paper discussed in Section 3 above. Thus "space reservations" are said to be provided to "accommodate quantified variations", which presumably covers added space margins for both maintenance and adaptability/Upgrade TL?

Set-Based Design, the focus of Parker et al., is an established design philosophy in recent NAVSEA surface ship programmes (Dorey et al., 2009). As Parker et al. conclude: "The purpose of using a set-based strategy is to make the right decisions first time…". This seems to be still very FoC design and build focused, with little apparent read across from the OR SSBN Fleet sustainability perception. So, unless "the cost, schedule and capability" emphasis stated gives prominence in the defining of "capability" to the sort of fleet level view of TL ownership that Coles (2012) clearly identified as necessary for the Collins Class SSKs, then again Availability at a fleet level seems to be under called by Parker et al. It is notable that when Coles addressed this for the Collins SSKs, he drew on his own deep involvement in nuclear submarine Sustainability for the UK SSN/SSBN Fleet (Coles, 2013). At the Appendix is a summary by Coles of his response to reading the first draft of the current paper.

The current author in his Submarine Conference paper (Andrews, 2017), pointed out how different submarine design was from even naval surface ship design, went beyond the direct "naval architecture" of submarine design to address the "fuzzier" aspects (see Andrews, 2022 for an explanation of this term) regarding the acquisition and ownership of such vessels. Much was discussed in that paper's Section 6 addressing acquisition, support and the danger of underestimating the risk/difficulties of "repeat design" from a submarine design perspective. Submarine support was seen as a costly endeavour, if (from the publicly available data on the Collins Class) the inadequate provision of resources to both sustain and retrofit necessary upgrades is not comprehended right from early-stage design (ESD). Yet again this author has argued that ESD of complex vessels is not to be rushed in the desire to get into detailed production design and build, as it is only in ESD that for "complex ships" the design team should and can adequately explore sufficiently comprehensively the full scope of capability, cost and risk, Through Life (Andrews, 2018) – and we should add **<u>to achieve the necessary whole class Availability</u>**.

Having by and large criticised even this last series of publications for their overly narrow single boat design focus, the last paper considered in this section (like Coles' papers already referenced (2012, 2013) takes a very broad overview of the ownership of those most demanding of vessels - nuclear submarines. The recent conference paper by Macdonald & Nicholl (2022) is entitled "Nuclear Submarines – the most complex endeavour in defence" and is directly addressing the Australian intent to acquire a fleet of SSNs, with the active support of the USA and UK. These authors argue from their experiences in senior UK MoD positions and subsequent leading roles in the naval acquisition industry, that the wider aspects (in part covered by the current author's comments on the "Fuzzier" half of naval ship design to an American audience (Andrews, 2022)) are what make the design and acquisition and TL ownership of nuclear submarines such a demanding and unique enterprise. They see the complexity as made up of the joint involvement of players from: industry; finance; military; societal; legal and regulatory; and political, and that "not everyone understands all this". Looking to the nuclear submarine endeavour that the Commonwealth of Australia is commencing to embark upon, they identify three critical success factors:

- The right mindset.
- An enterprise approach.
- Continuous investment, indefinitely.

While not arguing with their strategic analysis, that acquiring such a "capability" requires this national commitment, the author as a submarine designer, teacher and researcher and bearing in mind the insights from the analysis in the current paper that the key capability of Fleet availability needs great prominence, I would have liked a greater emphasis in the Macdonald and Nicholl's paper of the unique demands required of submarine designers designing such system of systems, which have to operate in extreme physical environments. Understanding specifically both the physics of pressure hull collapse and manoeuvring at speed (both of which this author has taught at Master's level from first principles) and then integrating the many sub-systems (from nuclear power plant through combat systems to the many fluid service systems – highlighted even at the Concept Phase by Figure 3) in a densely packed and finely balanced vehicle of several thousands of tonnes, which is also home to a hundred highly trained sailors, can be seen as a pinnacle of engineering design. And, I would argue, this specifically requires producing and sustaining an engineering cadre with submarine naval architectural knowledge and experience, if this "indefinite" endeavour is to be successfully pursued.

5. HOW CAN SUBMARINE DESIGN BETTER ADDRESS AVAILABILITY?

While accepting that achieving an acceptable level of availability for a fleet of submarines is a wider commitment than just "good ship/submarine design", whatever that might be taken to mean (see Andrews, 2022), there are suggestions already made in this paper that early recognition in the design process can greatly assist in enhancing the fleet availability when deriving for a new submarine design the "design style" (see Table 1 taken from Andrews, 2021). Table 1 under Design Style includes Adaptability (see Whybrow, 2014) but neither Availability nor Readiness, because it is still addressing the individual submarine rather than the Class/Fleet as a whole, even though it covers elements of the associated term "Sustainability". However in addition, as is clearly spelt out by Coles (2012), many of the issues to achieve adequate, or preferably "best in class", Sustainability/Availability/Readiness are of a very wide scope regarding the whole submarine enterprise of a nation, if that nation is genuinely operating or seeking to operate a modern class of submarines with sufficient "Fleet Readiness".

Table 1. Listing of Style topics relevant to a submarine design (Andrews, 2021)

Stealth	Protection	Human Factors	Sustainability	Margins	Design Style
Acoustic signature	Underwater weapon effect	Accommodation & Escape	Mission duration	Space	Robustness
Magnetic	Fire	Access	Watches	Weight	Adaptability
Infra-red	Shock	Maintenance levels	Stores	Vertical & Longitudinal centre of gravity	Modularity
Radar cross section	Damage control	Operation automation	Maintenance cycles	Power	Operational serviceability
Visual	Collision	Ergonomics	Refit philosophy	Services	Producibility
	Above water Weapon effect		Upkeep by exchange	Board Margin (future upgrades)	
	Corrosion				

Assuming the widest cultural and governmental commitments are made (as called for by Macdonald and Nicholl (2022)), then at the design level there are fundamental technical choices to be exercised and importantly these have to be made and held to, right from the earliest steps in the crucial first (Concept) phase of submarine design. Thus, one can have a clear availability objective, such as that for the US Navy OHIO Replacement Class': "same availability from 12 new as the 14 SSBNs being replaced" or a specific Material Ready Days for a given fleet, which is based on (and hopefully with improved availability) a previous class's achieved readiness.

However, there are some obvious measures with which a clear availability for the new class can be converted into specific design objectives and translated via a specific set of style choices (see Table 1) into technical features that are crucial in the initial design explorations of options and trade-offs (Andrews, 2018). Thus, space margins may need to be more generous than in past practice, where often arrangements have been too tight in way of equipment that in maintenance evolutions is critical to have easy access or even to be removed. There is also the problem of new equipment or different layout arrangements where the novelty may prove challenging in the life of the class. Adequate space margins in submarines are always fought over as the desire to keep to the limited pressure hull diameters for general space efficiency, means the only way to "gain" space inside the pressure hull is to make it longer. This then leads to consequential greater submarine weight, powering demand and probably BG and LCB impacts (Andrews, 2017). Further knock-ons, such as increased ballast tank capacity to maintain an agreed reserve of buoyancy, show how easy it is to resort to cramped maintenance spaces and make removal routes less than efficient. A focus on availability requires courage from the design manager to allow the submarine's size to grow and defend the likely hike in initial (build) cost by countering that improvement in fleet/class availability is actually the right measure of the overall project's VFM through life.

It has been projected that innovations, such as modularity (Whybrow, 2014), and novel designs, such as those regularly explored in the annual UCL Submarine Design Course (UCL, 2022), including such innovations as hybrid nuclear plant (Bradbeer, 2015), AUV MotherSubs (Pawling and Andrews, 2011, Purton, 2016) and Rim drive (Collins et al., 2015), need to be pursued if future submarines are to exploit new technologies. The author has argued this requires a DBB like approach to ESD used in all the above UCL studies (Andrews, 2018) so that more than gross weight and space balance is sufficiently explored in the Concept Phase. Given this conference's focus on Availability that exploration, for submarine innovation adoption, must not just be in terms of crude overall sizing and initial cost (UPC) but clearly address crucial architectural implications at the sizing stage, as is outlined in the following two paragraphs and Figure 3.

One aspect that recent research at UCL into submarine design has re-enforced a focus on maintainability, as part of fleet /class availability, is to tackle in ESD the implication of the host of distributed ship service systems (DS3). Thus, the DS3 can then be part of enabling key choices affecting maintainability to be explored well before the final concept design is fixed and taken into what is properly designated Feasibility. This is because the next design phase after the Concept Phase is to check the full technical feasibility to ensure that the agreed vessel's overall size and balance won't have to subsequently change, as this is likely to cause further size growth and/or deplete sensible margin provision.

The UCL research into distributed ship service systems (DS3) in ESD exploits the long standing UCL developments in the architecturally/configurational based approach to "ship synthesis" (i.e., the Design Building Block (DBB) approach (Andrews and Pawling (2003), Andrews (2018)). Mukti's (2022) research into DS3 in Early Stage Submarine Design was precipitated by the realisation by the current author that while DS3 contributions are substantial as a vital part of sizing a submarine, it has been difficult to do other than use simple sizing algorithms, such as the weight of a distributed system increases linearly with the length of the pressure hull or the pressure hull volume (Burcher and Rydill, 1994). This then inhibits introducing any variation in the distributed system's arrangement or reinforces the pressure to stick with technologies from past practice or having to adopt potentially excessive design margins for any novelty. The approach to DS3 that Mukti developed utilises a network flow analysis based on a surface ship application pioneered by Brown's research group in Virginia Tech (Parsons et al., 2020, Brown, 2022) that optimises efficient energy flow in power systems or in Mukti's submarine research each of 14 discrete submarine DS3 relevant mode of energy transfer. The marriage of the submarine internal architecture with the routing of the 14 systems, at a broad concept design level of definition, is shown in Figure 3and has been demonstrated by Mukti (2022). Such an investigation undertaken before proceeding beyond the concept design step, could be used to justify sufficient access for maintenance and for the removal of major items at refit and thereby enhance the confidence that the "design price" of improvements in unit availability could be justified as an investment in fleet/class availability.

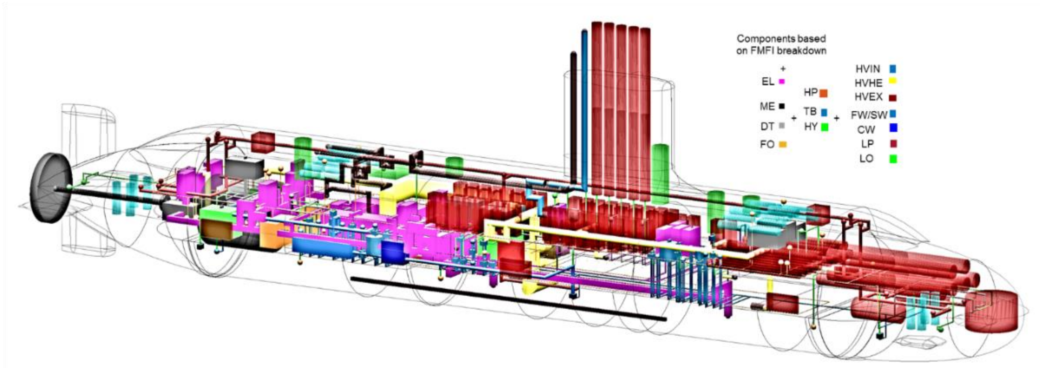

Figure 3. Mukti 's (2022) representation of the Distributed Ship Service Systems for a SSK Concept Design (Refined DS3 model in the third step of the Physical Loop method showing the progress in placing DS3 system by system in the 3D layout. There were 365 Design Building Block objects at component granularity and 472 Design Building Block objects at connection granularity level. The latter shows top level distributed systems routings for 14 services (DS3))

6. CONCLUSIONS

This paper has sought to clarify the conference's two themes of capability and availability, by arguing that availability has been seen, if at all, as part of ILS/Design for Support and, even then, has not been a primary design focus (based on the open literature on warship and, specifically, submarine design). Discussions on submarine design have focused on the main departures from the design of their surface rivals – or "targets' according to the submariners - and how to maximise performance or capability for the available affordability. All too often this has been done in terms of the design of an individual vessel (rather than the capability of a given fleet or class of submarines), whereas availability and readiness only make sense looking at the number of "available hulls" to the Fleet Commander. Or in the unique case of a SSBN force, sustaining the national deterrence capability.

Engineering designers have known for several decades that complex vehicles and systems of systems (submarines being in both categories) should be designed to the principles of Concurrent Engineering. Huthwaite's (1994) seminal text lists 40 "Ilities" or transversal/whole system characteristics sought in the design of complex systems – see also Table 1. Yet he does not include in his list of 40 that of availability, 'though in his defence he does include: Adaptability, Affordability, Deliverability, Compatibility, Installability, Recoverability, Recyclability, Reliability, Removability – all of which have some relevance to availability and more widely to submarine design. (Interestingly, two other clear omission from Huthwaite's "ilities" list are "maintainability" and "sustainability", so does this reveal again the Cinderella status of ILS/DforS in most engineering designer's considerations?)

It could be argued that the sense in the Commonwealth of Australia publishing John Coles' (2012) critique as well as his "get well programme", which highlighted the inadequate availability of their six COLLINS Class SSKs, has made the submarine engineering and design community properly aware of the importance of availability. But more than that, as I hope this paper argues, we have a new submarine design paradigm – we should not be designing a single submarine for its cost-effectiveness (however difficult even that is to encapsulate – see Hockberger, 1993) but rather seek to achieve the best VFM for a new class or even the whole submarine force, where the best sustainability/availability/readiness (for the resources sensibly deployed) is a primary objective for the new design of submarine. One might even take Fuller's "To dive; To move; To live; To survive" (Fuller, 1996) and add: "To be Militarily Available/Ready for the Maximum amount of the Class's Life in Service" – if that can be expressed in the three words "To be available"?

7. ACKNOWLEDGEMENT

This paper was started in response to the topic of Availability posed for Submarines 2023. I shared the draft with my close friend and erstwhile RCNC colleague, John Coles, knowing his leadership in particularly of the Collins Class Sustainability Study that he led in the last decade. John kindly critiqued my first draft and, while the current paper is entirely my authorial responsibility, it has been very significantly enhanced by his comments, many of which I have attempted to incorporate – not least John's emphasis on Sustainability (rather than Availability) and even more so his identification of the need to "maintain the design intent" with the watch word of "readiness' – allowing me to quote from Hamlet!

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APPENDIX - COMMENTS ON AVAILABILITY BY JOHN COLES

I have commented on the paper and consider it is over focused on design. Availability or readiness is quite a different capability - it is the sum of wide range of outputs or enablers undertaken in the procurement process - not necessarily directly linked to the development of the design itself. It is much more dependent on key enablers - reliability of machinery is key, so making the correct equipment selection is the issue not specific design issue. Often the design solution (to improve availability) has been to change the machinery - and that is not directly a whole boat issue unless the space demand is significantly reduced - and that would be part of the design process. But you can improve availability in service without undermining the initial design solution. More broadly I suggest that other factors are far more important - these relate to infrastructure, spares availability, a knowledgeable naval base/industrial structure and organisation, etc. All these are not the purview of the naval architectural features of a design but the managerial influences outside.

You will know of course that my work on Collins did not come to any view about design issues affecting the availability, although there were some. The design issue of importance to come out of my review was the absence of a proper system for maintaining the design intent. The greatest improvement in the Collins Class performance was to reduce the time spent in maintenance in major overhauls (by 33%) reduce overruns in planned maintenance (better management of material supply) and improved reliability of some key equipments - none of these issues are related to the design itself - which is under the right leadership and is extremely capable.

Perhaps worth saying surface ship both commercial and naval often have as much as 340 days per year availability - especially cruise ships - and this must be embedded in the design and support infrastructure. Two naval classes had contractual availabilities of over 320 days per year will payment depending on performance. Theses naval ships were at the simpler end of naval vessels and to achieve this performance the crew was at least (from memory) 1.5 times the complement. I doubt if submarines could get as high as this but SSBNs do have a high availability - although I doubt if anyone would release such figures. I do not know what is being achieved today for the RN SSNs because that is not in the public domain.

Finally, the other factor I brought out was the need for all the key agencies helping to deliver availability work as a 'collective enterprise' - In Australia this was achieved because all the key elements were funded directly by the Australian Government - it was the collective leadership that help to deliver my recommendations.

From my point of view, you over focus on design in delivering availability whereas I believe it is more influenced by other external and none design issues. You need a very compelling design change to radically alter the availability.

I hope this helpful. The issue to get across is that availability or readiness need to be inputted to design process with much greater focus - and we can both agree on that!

AUTHOR'S BIOGRAPHY

David Andrews FREng, PhD, FRINA, FSNAME, RCNC was given a new Chair in Engineering Design at UCL in 2000, following his early retirement, when a Director (1*), from the UK Ministry of Defence. His early career in the RCNC included several postings in both in-service conventional and new construction nuclear submarine design sections and as Section Head for the VANGUARD Class Structures and Hydrodynamics Design Section. He was subsequently Head of Preliminary Design responsible for all initial naval design studies, including for the Future Attack Submarine. From 1993 to 1998 he was appointed the MoD Professor of Naval Architecture at UCL, where he directed the MSc in Naval Architecture and the post-MSc Submarine Design Course. In 2001 he set up a new Design Research Centre in the Department of Mechanical Engineering, which is focused on CASD and the design of physically large and complex systems. He is a Fellow of RINA, a former Vice President and previous Editor-in-Chief of the IJME. In 2000 he was elected a Fellow of the Royal Academy of Engineering and was until 2022, the International Chair of the triannual International Marine Design Conferences. In 2020 he was awarded RINA's highest award, the William Froude Medal, "for his contribution to the field of ship design" and in 2021 awarded the SNAME David W.Taylor Medal for Lifetime Achievement.