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THE EXPANDING SCOPE OF SHIP DESIGN PRACTICE

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ABSTRACT

As the former International Chair of IMDC, the initiator of the continuing series of IMDC State of Art (SoA) Reports and the lead author of most IMDC SoA Reports on design methodology from 1997 to 2018, the author has both pioneered and observed an increasingly broader scope in the practice of the design of particularly complex vessels.

The paper commences with reviewing some key publications, not just to recent IMDCs, that have tracked the manner in which "ship design" (in the broadest sense) has become more sophisticated – especially in the crucial early stages of design. The diversity of ship design practice, not just due to computer-based methods, is readily observable. Moreover, the impact of computer aided design in ship design has not just been to better analyse ship performance (e. g. in hydrodynamics, strength and ship infrastructure systems behaviour) but also in the increasing use of graphical tools and design methods to enable "better ship design". In a growing number of, mainly, academic centres, but also in some government agencies and design consultancies, there is a clear desire to better understand how to design "ships" and to manage the ship design process, especially for the most complex and novel classes of vessels. In particular, the objectives being sought when conceptualising and synthesising a range of ship options (as part of the requirement elucidation approach) in an ever-increasing scoping of the relevant issues, amounts to developing a more holistic approach. This is not just due to an increasingly complex ship acquisition and ownership environment, but also due to environmental and socio-economic (especially system safety) concerns. Overlaying all this are the opportunities or the spectre of Artificial Intelligence (or perhaps more immediately those of Machine Learning) and its likely impact on engineering practice as well as those other professions in the "marine design enterprise". The paper concludes by emphasising that while ship design has distinct differences, when compared with most other large scale engineering design practice, the lead ship design profession of the naval architect has somehow to deal with this expanding scope in the practice of "ship design". This means the education and on the job development thrust must broaden if the ship design profession is not to be side-lined into acting as mere hull engineers. It is argued, such a specific role will be more vulnerable in an increasingly Machine Learning dominated future, than the holistic ship creating and systems architectural alternative. Finally an ambitious vision for future ship designers is given alongside a summary of the specific main contributions by the author to ship design methodology.

(Creativity is) "The production of new knowledge from already existing knowledge and – accomplished by problem solving" *Arthur I Miller: "The Artist in the Machine: The World of AI Powered Creativity", M.I.T. Press, Cambridge, MA 2019.*

"No theory, no ideology, no set of rules can deal with human complexity, human sensitivity or vulnerability" *Sir Ove Arup: "What I believe" undated in "Ove Arup: Philosophy of Design", (Ed. N Tonks, Prestel, London, 2012)*

KEY WORDS

Ship Design Process; Ship Design Practice; Computer Aided Ship Design; AI; Machine Learning.

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1. INTRODUCTION

1.1 Preamble

It is the opinion of the author, from a close involvement in the triannual IMDC conferences for more than the last two decades, that the scope of the practice of ship design has expanded in recent years. This is investigated by looking back even beyond this timeframe to the commencement of such considerations, which could be said to have been initiated by Stian Erichsen, the first chair of what was first designated as the International Marine Systems Design Conference series from the inaugural IMSDC 1982 conference in London. This conference resulted from a precursor symposium in 1979, called by Erichsen in Trondheim, with contributions from twelve eminent practitioners in the field of "marine design" (Erichsen,1979). After the initiation of the IMSDC series, the first conference followed a similar pattern to that of 1979 with eleven invited authors to present their versions of the state of the art in, essentially, ship design, which was seen as the essence of "marine systems design practice". The term 'marine systems" reflected Erichsen's particular view that the bulk of merchant shipping can be seen to be part of larger transportation systems, for bulk goods, like petroleum products, or containerised manufactured items. The conference title also reflected a wider engineering design paradigm, that of systems engineering, which was first adopted to manage large military programmes (including submarines and surface vessels) in the post Korean War NATO-Warsaw Pact conflict. A similar paradigm may shortly arise with the design practice for complex systems due to current rapid developments in Artificial Intelligence (AI) or at least Machine Learning (ML) and so it seems necessary to address the expanding scope of marine design at this point.

IMDC conferences have been a good (if not perfect) mixture of input from industry as well as from academia involved in "marine design' and with a focus on the ship design process and practice. Thus, we should take Erichsen's "whole systems" stance as a broad measure and also go beyond classic naval architectural views of ship design. The current author introduced the distinct conference feature of State of Art (SoA) reports into the 1997 IMDC, under the IMDC chairmanship of Erichsen's successor, the late Pratyuch Sen. The SoA reports were seen as a way of reflecting, not just rapid advances in computer aided design but also scoping the increasing diversity of "ship" types (including floating offshore structures) and many design approaches being introduced, including a realisation of the widening scope of what "ship design" should encompass. This broadening scope came from a view by the author, who having had two short (four years each) "secondments from the UK Ministry of Defence (MoD)" to academia, which included authoring a ground-breaking PhD (Andrews, 1984), while teaching at UCL, returned permanently to UCL in 2000 after a career of three decades in naval construction in the UK Ministry of Defence (MoD).

Thus, the author also presented at IMDC conferences over more than two decades several IMDC Keynote papers, including one in 2012 asking "Is Marine Design now a mature Discipline?" This issue of the emerging discipline in naval architecture of ship design was in part behind the initiation of the wider SoA Reports and specifically those on Design Methodology. Two years before that 2012 Keynote, I reviewed for the RINA Anniversary "150 Years of Ship Design". Both perspectives drew on 35 years designing a very wide range of vessels for the British Royal Navy followed by over two decades leading research on an innovative "inside-out" approach to the design of complex vessels, which culminated in 2018 with writing a Special Edition of the RINA Transactions (Andrews, 2018a). This was uniquely commended by the RINA Council and still provides the basis for me to argue that not only have the types of marine vessels continued to become ever more diverse, but also the practice of "ship design" has expanded well beyond traditional (apparently simple) approaches to ship synthesis, such as the ubiquitous "design spiral" that I have criticised as being simplistic and misleading.

While naval ship design might seem to be a rather specialised experience of "marine design" (especially when that includes the highly demanding and specific domain of nuclear submarine design), in terms of the types of designs undertaken, it can be seen to be highly diverse. This is because those "ship" types range across naval combatants, submarines, specialist large naval vessels, naval auxiliaries (with tanker and cargo carrier characteristics) and novel vessels, such as a royal yacht and procuring the first ocean going trimaran ship. My "naval ship" design experience also encompassed all phases of ship design "from cradle to grave", including being the Design Authority for a large part of the Royal Navy's surface fleet (SAOS, 2020). This range of experience is summarised in Appendix A at Table A1, where my role for each of 18 separate designs for the Royal Navy is identified and gives my view as to "what drove each design" and the "key lessons learnt from each of those design involvements". The latter set of summary statements was produced to reinforce the message that such ship design practice is already highly diverse in scope.

I was able to undertake relatively early research in CASD (1980-84), when still practicing "ship design", while a permanent move to academia in 2000 enabled more extensive research to be conducted into ship design methods, types of ship design and design issues, many of which have been presented at IMDC conferences over the last two decades. This research is briefly summarised, with appropriate detailed references in the major monograph on the early-stage design of complex vessels produced as a Special Edition of IJME/RINA Transactions in October 2018 (see Sections 6.2 and 6.3 of Andrews (2018a) for example UCL projects). A further justification for the current paper focusing on the expanding scope of ship design is due to the likely impact of the advent of the specific form of Artificial Intelligence (AI), namely, Machine Learning (ML). The implications for the practice of managing the design and build of Physically Large and Complex Systems (PL&C) Systems has already been outlined for the architectural profession (Bernstein, 2022). Possible implications for the design and project management of acquiring complex vessels are addressed later in the paper, where the future practice of ship design is considered once the nature of the postulated expansion of ship design practice has been explored.

1.2 Lessons from IMDC State of Art Reports

Having persuaded the IMDC chair to introduce the SoA Reports, the first set of reports in the VI IMDC (Andrews et al., 1997) was clearly scene setting and of an overall reviewing nature. Consequently, the process was not revisited until the IXth IMDC (Andrews et al., 2006), and since then, there have been SoA Reports at each IMDC (Andrews et al., 2009; Andrews et al., 2012; Andrews and Erikstad, 2015; Andrews et al., 2018; Erikstad and Lagemann, 2022). The first SoA Report on Design Methodology (DM) consisted of ten separate sections in two halves: the first five could be considered generic (e.g., general design theory, systems engineering, preliminary ship design methods, safety) while the remainder covered the design of specific vessels, from passenger ships, unconventional vessels, offshore structures, to naval ships and submarines). Notably, the latter sections did not include sections on bulk carriers and container ship design, despite that being the original intent. Subsequent SoA reports covered "ship design methodology" as well as specific ship design issues that were usually on topics of particular interest to the maritime sector of the hosting country (e.g., Offshore Engineering for the USA in 2006, Artic Design for Finland in 2018). The introductions to the 2015 and 2018 SoA reports on design methodology provide more detailed summaries of the various previous SoA reports, each of which included copious lists of key publications.

Before passing on from the IMDC SoA (DM) reports and the extensive source they provide on marine design practice and how it has expanded in scope over recent decades, it is worth recalling the nine issues that the first SoA DM report raised when presented. These were in brief: -

- (*There are)* "Different models of the (*ship*) design process;
- Models of design/design practice (*are*) too academic;
- Concept tools too often ignore context;
- Design on the *(computer)* screen needs traceability;
- Concept design (is) vital, noting (*the*) role of decision-making methods;
- Concept *(Phase)* in commercial ship design is too short;
- Method vs. methodology needs defining;
- *(It is wise to)* look at the Science of Design, elsewhere;
- A formal taxonomy (*would help*), while avoiding rigid design procedures."

This set of concerns can be contrasted with the last SoA report (Erikstad and Lagemann, 2022), which saw four "main evolutionary tracks" in marine systems design methodology: a holistic optimisation strategy; a systems engineering based approach; a set-based strategy; and configuration based design. Each of these tracks were then allocated to 34 PhDs in "marine design" completed from 2016 to 2022 in nine universities in Europe and USA. Erikstad and Lagemann's four tracks are revisited below, as are the nine bulleted issues above, at the end of the paper, to see if they cover the extent to which it is surmised that the scope of marine design has truly expanded.

1.3 Is Marine Design now a Mature Design Discipline?

A paper with this title was presented by the author to the XIth IMDC (Andrews, 2012a) after thirty years of IMDC and some fifteen SoA reports. This keynote started by asking "why this question needs to be posed, both as a general issue and at this time at IMDC", furthermore, asking "haven't ship designers been perfectly happy designing ship for centuries?" This was addressed (through reviewing key IMDC papers and certain other selected publications) by answering the following points: -

a. What actually is marine design?
b. Has three decades of consideration (in the tri-annual IMDCs) established marine design as a coherent and accepted body of work and practice, vis a vis the other two naval architectural sub-disciplines (those of ship structures and ship hydrodynamics – *with their own regular international conferences*)?
c. If ship design is a mature discipline, is there a clear route towards marine design's future development with the assumed aim of providing "better ship designs" undertaken by "better ship designers"?"

In fact, the last issue has been more recently addressed in a more satisfactorily manner, at least for naval vessels, in Andrews (2022) which followed on from the last IMDC. A summary of the 2022 discussion of "good ship design" is covered in Section 4.3.

The 2012 IMDC paper on whether marine design was now "mature" reviewed IMDC conferences, not just from the State of Art reports, but also considering several keynote papers, such as Andreasen's (2003) vision of design methodology which he spelt out as threefold: -

- "By what methods do we design?
- What are the theories, and
- Scientific basis for this?"

Also, the 2012 IMDC paper drew attention to Nowachi's (2009) IMDC Keynote on "Marine Design Methodology -: Roots, Results and Future Trends" from over five decades of involvement, to which it seems appropriate to return, when this paper ends by consideration of the future of ship design. The 2012 keynote also discussed several publications that had been recently produced that were seen to be highly pertinent to the already wide scope of ship design practice. Two of those were lecture texts made available to the ship design fraternity (Lamb (2004a) and Yang (2004)). Both provided extensive lists of "key references" and can still be seen to be useful in parallel with the IMDC SoA reports and their copious references. The first of these sets of lecture notes were by the editor of the two volume multi-authored SNAME book "Ship Design and Construction" (Lamb, 2003, 2004b), which also addresses some fundamental design issues, while Yang's presentation gives a historic timeline (reproduced in Andrews (2012a) IMDC keynote at Figure 5) of "Design Theory" on the "practical design of ships". This starts with Baker (dated 1942) and ends at 1995, which now poses the question as to whether we need an up-date. Finally, mention should be made of the 26 "models of the Ship Design Process" collected in the X IMDC SoA DM Report (Andrews et al., 2009).

1.4 What can be learnt from "150 Years of Ship Design"

The above title refers to a RINA Transactions paper (Andrews, 2010a), which (as part of RINA's 150th anniversary) reviewed 150 years of ship design published in the longest series of naval architectural articles. This review pointed out that there had been immense changes in ship design in that period. This was ably reinforced by the companion paper by Buxton (2011) entitled "Enabling Technology and the Naval Architect 1860-2010". Notably papers in the first 100 years of that review were seen to be largely descriptive of the many technological advances of the day, however there was seen to be a distinct broadening of considerations of ship design in more recent years. Thus, in the latter part of that 2010 review it was seen as sensible to draw a distinction between the earlier and more recent papers on ship design – not least due to the radical change in ship design practice arising from the advent of electronic computers. Six specific categories were thus adopted to review the progress of ship design in the last five decades (up to 2010): -

i. General design reviews, where developments across a range of ship types were undertaken, such as naval reviews (e.g., Purvis 1974) to the evolution of the modern cruise ship (e.g., Payne 1990, 1998);
ii. Specific merchant ship designs, with probably the most notable being Meek's series (1964, 1969, 1970, 1972) outlining, through four series of designs, the epoch-making transition from his "ultimate cargo liner" to the modern container ship;
iii. Specific naval designs ranging from the first GRP MineCounterMeasures Vessels (Harris, 1980) to submarines (Wrobel, 1985), new aircraft carriers (Honnor & Andrews, 1982) and the Danish Fishery Protection Vessel (Watson & Fritis, 1992);
iv. Novel ship types, showing the explosion in types of marine vehicles from LNG vessels (MacGregor et al., 2006) to a wide range of unconventional hull forms (e.g., Semi-Submersible Drill ships (Winters et al., 2001));
v. Specific design issues, ranging from economics (e.g., Goss, 1965 and Rawson, 1973) to accommodation (e.g., Cain and Hatfield, 1979 and Andrews et al., 2008) and the impact of electronics (e.g., Gates & Rusling, 1982);
vi. Design methods and practice, which given the stance of this paper, deserves more extensive consideration here and can be seen as a direct consequence of the computer's ubiquitous impact on ship design practice and (in recent years) the parallel need, or desire, to better understand the ship design process.

While these six categories are useful to see the expanded scope of ship designing over recent decades, in design methodological terms it is the last of these that is now considered. The early consideration of CASD was noticeable for considerable discussion from the RINA membership of each development. From 1977 (almost commensurate with IMDC's origins), papers on ship design methods and design approaches were in the RINA Transactions: notable on the merchant ship side was Watson and Gilfillan's (1977) "Some Ship Design Methods" to be seen in contrast with both Canadian and British naval originated papers, including the author's early 'configurationally/inside-out" synthesis proposals (Andrews, 1981, 1986, 2003a). There were also papers on thematic design, such as Brown's (1993) "History as a Design Tool" and Woods' (2008) yacht design paper. Also worth mentioning are the seminal papers by van Griethuysen (1992, 1994), on "monohull warship geometry" and the most detailed presentation of the early-stage design of a specific naval combatant option, using the UCL Design Building Block (DBB) approach (Andrews and Pawling, 2008), which also provided an extensive bibliography of preliminary ship design methods. The final group of papers on the practice of ship design cover the years 1993 through to 2009 and are mainly on naval ship design practice internationally but also includes one on maritime rescue craft (UK RNLI paper: Cripps et al., 2005).

The brief outline above, with a few selected examples from the fuller listing in the 2012 paper, is seen as further justifying the immense scope to be encompassed by any consideration of the nature of marine design as currently practiced and, by implication, the difficulty in arriving at any clear understanding of marine design methodological assessments. It needs to be said there are other summary articles that also provide similar reviews of ship design to that in the 2010 RINA review, such as Benford (1993) (see also TransSNAME 1993 Vol.101 for various Centenary papers, not just on ship design) and Nowachi's (2010) paper in a general CAD publication. However, as the rest of this current exposition suggests, there is no reason why common themes should not be identified, if we are to look forward to future needs and developments in our discipline, as suggested by the third of the issues identified in Section 1.3.

1.5 Initial conclusions on the expanding scope of ship design practice

Even before the main disposition in the rest of this keynote, it is possible to discern the degree to which ship design methods and practice have already expanded greatly from the traditional design approaches used by shipping companies (and then shipyards), for merchant shipping, and by navies and naval yards for warships, even prior to the immense changes in very recent decades. However, there still seem to be some constants in the maritime sector, that may or may not finally change. I have in mind the fact (aside from some very few radical designs touch upon in the fourth category in the previous sub-section) that the following are still relevant: -

i. The implications in not resorting to full-scale prototypes, unlike automobiles and aircraft design and manufacture, though some might argue that the advent of the Digital Twin facility means we now have virtual prototyping?
ii. The lack of investment in ship design, when compared to the development of naval combat systems and even general ship equipment (especially for recent main machinery developments driven by carbon reduction pressures);
iii. Both of the above points can be seen to be consequences of ship design being characterised by risk adverse shipbuilders, who undertake the bulk of ship design, if this is to be judged (perhaps questionably?) by the extent of engineering construction resources deployed. This applies across the ship design domain and has been made worse in the naval sector by the adoption of Prime Contractorship (Andrews, 2018b). While there has been some signs, such as the adoption of alliances (as for the UK Queen Elisabeth Class aircraft carriers (Coles, 2007)), it is the case the merchant shipping sector has not adopted the Cost Reduction in the New Era (CRINE) strategy (Cox and Newland, 2000), that the UK Offshore Industry introduced over two decades ago, to reduce cost risk margins being accumulated down the sub-contracting ladder, which had led to such projects becoming unaffordable.

1.6 Outline of the rest of paper

This consists of five main sections, each divided into several sub-sections: -

- Diversity of ship design and impact of computers and CAD;
- Trying to understand ship design and the ship design process;
- Seeing the objectives in ship design as holistic;
- The future impact of AI on design;
- Conclusions – four main topics with two appendices.

2. DIVERSITY OF SHIP DESIGN AND IMPACT OF COMPUTERS AND CAD

2.1 Types of "ship" roles

One reason why ship design has continued to increase in scope is the ever-expanding types of "ships" (or better marine vehicles/vessels/structures). As ever we are presented with a typological challenge. Erichsen (1998) talked of marine systems design, and this was right in so far that all marine entities (ships) are part of some larger marine system (such as bulk cargo transportation or naval fleets). But when it comes to designing, our focus (hopefully with a growing awareness beyond – because that is part of the expansion in the scope of ship design) is largely on the 'ship". It is clearly a floating vessel (and not a platform – see argument in Andrews (2022)) and could be a (mobile) vehicle from a systems perspective, ‘though hardly to be seen as similar to much smaller land and air supported vehicles. The latter two types of vehicles have comparatively limited endurance and sustainability, while offshore structures have limited mobility, but they do float and so are not civil engineered fixed structures, even if “planted in an inhospitable seaway”.

“Ships” are often divided up into consideration on the basis of their owners’ motivation for such a large investment in money and human resources. Thus, bulk carriers, container carriers, passenger carriers (blurred by the difference between essentially acquired for entertainment or ferrying) are about delivering “a cargo” ocean wide through ports, while other ships (including the highly diverse set of very expensive naval vessels (see Table A1)) are designed to provide a service “at sea”. That “service” is often motivated by a need to deal readily with unpredictable events, be those supporting offshore floating/fixed facilities or the extremes of disasters ashore/policing at sea/outright warfare. Thus, in simple terms there are ships which are designed to be part of a larger transportation system and those (often more highly diverse and without clear measures of merit to guide design choices) which are essentially service vessels, where the design problem could be said to be more “wicked” (see Section 3.3).

This very wide range of “roles” has expanded over recent decades to deal with new markets and needs, by largely newly emerging national and commercial imperatives. It is likely with growing world trade, challenges of environmental change and political upheavals, that further discrete “ship types” will emerge. Not least, ship design is driven by the current search to mitigate the effects of carbon (and other environmental impacts), while there remains the general motivation (with the somewhat bizarre exception of mega yacht owners) to maximise the capability (however that is defined – see Section 4) for the expenditure able to be provided in order to acquire and operate new vessels.

2.2 Types of “ship” forms

Having said there are many roles that ships undertake, which perhaps justifies the need for a better understanding of ship design, there is an aspect of ship design, which can be said to add to the complexity of the ship designer’s challenge. It can be argued that few other designers of complex systems seem to have, alongside general engineering design demands, the level of choice that the ship designer has in the form of their mobile floating structure. It needed an engineering design theorist, with no marine design background, to reveal this explicitly at the second IMSDC. The late Stuart Pugh, author of many publications on “Total Design” (Pugh, 1996), presented a paper entitled “Systematic Design Procedures and their Application in the Marine Field” (Pugh, 1985), which is still worth reading, however I particularly want to quote his view that for some industries “true conceptual design in totality is no longer necessary”. Such designs are what Pugh called conceptually “static” and this applies to the design of automobiles and aircraft but, much to Pugh admitted surprise, this is not the case for ships.

Why this investigation of the “dynamic choice” of form is not done as a matter of course in most ship design is worth debating and in my seminal monograph of 2018 (Andrews, 2018a) I strongly suggest the Concept Phase for complex vessels should, as a matter of course, explore the solution space and do so much more widely than is usually the practice. It should also, in so doing, recognise that different conceptual options require different approaches to obtaining the first balanced “ship” concepts. Thus, clearly there is no single ship design process, if we are talking of synthesising a ship solution that may be subsequently developed. This is discussed further in the next sub-sections.

2.3 Types of “ship design” practice

Depending on who wants/funds a new “ship” and who undertakes the design process and whether they are involved throughout the subsequent ship design process, including the build/assembly of the completed vessel and maybe even through in-service to disposal, it seems clear that ship design practice varies greatly. Furthermore, the appropriate ship design practice in each new ship acquisition is fundamentally dependent on the intent behind the acquisition process for each design considered.

In the IX IMDC State of Art Report (Andrews et al., 2006), of the 26 models of the ship design process already mentioned, there were six versions of the Design Spiral. When it comes to most textbooks on naval architecture dealing with the initial design of a new ship, they resort to the “Design Spiral”, as do many designers writing of ship design. This is in a way odd in that its originator, Harvey Evans, was an American ship structural academic and presented, in what he edited as a text launching the modern (probabilistic) approach to ship structural design (Evans, 1975a), a figure, which is not of the ship design process but a ship structural design process, which he showed as a spiral. Evans had already produced a wider ship design spiral seeing “structural design itself is but a part of a larger whole made up of spirals within spirals” (Evans, 1975b). So, the structural spiral is just one of many? That this was taken up by designers of whole ships and applied as a single spiral to not just initial ship design but often the whole ship design process through to build, without much obvious debate, seems a little odd to this author (see Pawling, et al., 2016) and to other actual design practitioners, given actual ship design is nothing like that.

The attraction of the Ship Design Spiral seemed to be that a spiral shows the observed iterative steps undertaken, apparently in a sequential manner, in order to size a new design option through balancing weight and buoyancy, powering and resistance, and, probably, just initial intact stability. Thus, the spiral implied a fixed sequence, one that at best was strictly only applicable to certain conventional monohulls, took no account of any external activities, including inputs (or even decisions) from various stakeholders (including sub system designers), and proceeded in a fixed sequential manner without any decisions or changes to the proscribed sequence. All of which is clearly unrepresentative of real ship design practice – certainly at the more sophisticated end of the spectrum of "ship design". This highly simplistic view of ship design will be compared with both the author's decision-based strategic process and a more holistic human centred process originating from the author's more philosophically based vision of ship design (i.e., Requirement Elucidation driven and "inside-out" focused (Andrews, 2018a)).

2.4 The Impact of computers on designing "ships"

It was an eminent Dutch naval architectural academic Gallin (1973) who quite early on said "ship design without computers is no longer conceivable". I take it that he was referring to the fact that most engineering analysis, which I, like most engineers of that ilk in my earliest "calculating posts" (see Table A1), learnt to do engineering analysis using mechanical calculators. However, this century old practice rapidly transitioned when the author acquired the UK MoD's first hand-held "pocket calculator" (using Reversed Polish notation). This enabled me to carry out the necessary calculations on site while conducting the Trim and Inclined Experiments on submarines coming out of major refits, an evolution that almost rebuilt each vessel's internal outfit. Just a few years later, we were using large "main frame" computers to undertake finite element analysis (FEA) of whole ship structures (Honnor and Andrews, 1982), while still hampered by the lack of pre-processors and post-processors to facilitate the management of what then seemed to be a vast amount of data. Clearly, engineering analysis has come on by leaps and bounds and has fundamentally changed how we do the analytical side of engineering design.

One issue concerning modern presentation of results of what can seem to be "black box" analyses, is the apparent plausibility of superb results presentations, that leaves the designer with the need to understand the veracity of their modelling of reality. Furthermore, there is the question as to whether the specific sophisticated analysis undertaken is appropriate to the investigation of that design for the likely environmental behaviour, to which the overall ship system will be subjected when in service. When it comes to the specifics of, say, designing a hull form and checking that form is right for the likely response of the whole system (rather than just specific strength concerns addressed by (say) FEA) we can, for example, now impose the likely statical stability response at the press of a keyboard button. While the geometry of the underwater form is now easily modelled, the assumption (until quite late in a design) as to where the mass centroid of the complete vessel lies (particularly vertically), remains a "guess" by the human designer, a typical example of ship design uncertainty.

2.5 The impact of computer-aided ship design on "ship design"

I have observed through my career, as firstly a designer of naval vessels (see Table A1) and latterly as an academic engineering researcher and design philosophiser, that the advent of computer graphics, linked with the appropriate mathematics and physics applied to each design, has enabled the designer to open up the ship design process. However, this immense capability will only work to produce "better" designs if we resist the misapprehension that CAD doesn't mean the computer does design but rather it **Aids** the designer. Thus, the naval architecturally aware designer has to provide the creative input into the design evolution of a new whole ship design and do so from a true position of understanding the ship as a whole. To do so means other players in the ship design process must accept that the ship design experienced naval architects is **the** designer, being the one who makes most of the crucial ship design decisions. Those key design decisions at a generic level have been spelt out several times through extensive appendices in the author's key papers (Andrews, 2012b, 2018a).

Given a broad view of the development of ship design since the advent of CAD, and the increasingly ubiquitous implications of Data Driven Design (D3) (Gaspar 2018) with the further implication of using Machine Learning tools, this future needs to be debated. This D3 view was made as one of the published responses to my major exposition by on the sophistication of early-stage ship design (ESSD) (Andrews 2018a). The effect of CAD and project management techniques (such as systems engineering) on how ships are designed have not been broadly debated. A clear exception to this is in the naval ship design field where the series of papers (in SNAME Transactions and US Naval Engineers Journal) over several decades by Keane and his colleagues (Keane et al., 2009, Keane and Tibbitts, 2015, 2018) have addressed US naval ship design practice. To a degree, this has been matched by various (largely RINA) papers by the current author looking at the procurement practice for UK naval vessels (Andrews, 1993, 1994, 2016, 2018b). Both sets of publications on this topic were drawn on in a recent SNAME SMC paper (Andrews, 2022) and some of the relevant arguments are also addressed in the current exposition.

It is provisionally concluded from this opening review of the current state of ship design, that ships and their design should be seen as a highly diverse set of engineering endeavours, and furthermore that the diversity of product and process is becoming ever greater. So, are there lessons to be learnt as to how we, as ship design practitioners and researchers in pushing the boundaries of these endeavours, might better understand what we do and thus how it can be made more resilient to cope with future challenges?

3. TRYING TO UNDERSTAND SHIP DESIGN AND THE SHIP DESIGN PROCESS

3.1 Ship Design is part of Engineering Design which is part of wider Design Practice

Seeing marine design in a broader design context has been part of the IMDC approach since 1997, when State of Art Reports were introduced, and particularly the Design Methodology series, which has included consideration of developments in the wider design community. This was consistent with earlier IMDCs inviting theoreticians in engineering design to present their broader perspectives (see Pugh (1985), mentioned in Section 2.2, and Andreasen (2003)). Such wider design visions were also reflected in my first methodological paper (Andrews, 1981), which looked at a range of design tools and techniques as part of a "creative approach" to future ship design. Thus issues, such as design thinking (Engholm, 2020), or which see design as a creative process (Nelson and Stolterman, 2012) and design philosophy, beyond marine design, are considered worth keeping an eye on. This is not just in case some insights from designers in other challenging domains could provide insights but also that (given this paper's theme) the likely developments in general computer aided design will have impact on our design practice.

This all comes under the umbrella of "Design Methodology", where the use of the term methodology is not the adoption of a fancy word for a new method but "the science of method in scientific procedure" (Chambers, 1971), which means consideration of such methods at a meta-level. Given many engineering design practitioners "just want to get on with designing" and thus too readily adopt the first convenient model (e.g., the ship design spiral), there has been some questioning of this broader view of design methodology. As a view from two eminent engineering thinkers, I have previously presented Finklestein and Finklestein's (1983) four specific rebuttals to those objecting to this intent to raise the intellectual and philosophical vision of engineering design. This I presented to IMDC 2012 (Andrews, 2012a) with my response addressing the relevance of these issues to ship design, and is reproduced as Table 1 in order to discuss it further in the light of the theme of the current paper and the major changes expected to engineering (and architectural) design practice from AI related developments.

Table 1: Finklestein and Finklestein (1983) Justifying Design Methodology and Andrews (2012a) Comments

	Objections to Design Methodology	Finklesteins' Answers	Relevance to Ship Design
1.	Design is intuitive and creative any methodology stifles creativity.	Design not purely intuitive, it is amenable to understanding.	Good ship designers often intuitive but have clear approach – a Methodology.
2.	Methodology constrains the designer.	Methods are sets of rules and alter the context.	Rules are used but awareness is important.
3.	All methodologies have inherent value systems.	Value systems are inherent the important thing is to be aware (of their influence).	Value systems lead to different design solutions by different designers.
4.	No evidence of applicability of design methodology.	There is a wide number of design methods used in different fields.	Ship designers still naval architecture dominated (S^4) and need ship architecture.

Taking each point in Table 1 in turn: -

1. While a good ship designer (however that might be defined and determined - see next section) can be intuitive (probably enhanced by experience), they need to adopt a clear approach, which ought to be based on methodological awareness. This becomes harder given changes to both the constraints (see Table 2 of Andrews (2018a)) and to the practice of ship design, which is seen to be happening ever more rapidly;
2. Ship design "rules" have been used, especially when new projects have significant uncertainty. While databases are increasingly available, they also introduce dependencies on "black box" tools and on databases with likely opaqueness. Awareness by designers of such issues becomes more essential and hence it seems even more necessary to adopt my decision-making strategy, which is summarised by Figure 1 at Section 3.2.
3. So as ever, value systems (inculcated by each designer's culture and education, which need to be seen in the widest sense, not just in university degrees obtained) mean there is a distinct "style" (which is discussed in the next item) implicit in each design solution, or, at a minimum, the (unquestioned?) adoption of a default style and practice.

4. Currently ship designers approaches to a new ship design are, for very good historic reasons (i.e., both of safety and a designer's limits to understanding), still dominated by the traditional naval architectural sub-disciplines (i.e., the first four of Brown and Andrews "S^5" issues - see Figure 1 in Brown and Andrews (1980)). However, a significant portion of this is becoming highly amenable to Machine Learning (see Section 5) and therefore the less ML amenable internal architectural drivers will become a greater focus for the ship designer. The growing need to put the ship internal configuration together more coherently, further justifies my advocacy of an "inside-out" approach (Andrews, 2018a). This is not just to achieve a better design synthesis but also to guide the development of the subsequent design's full definition.

Previous IMDC SoA design methodology reports have reported on what seems key wider design discussions beyond the maritime domain to provide potential insights, as the scope of ship design continues to broaden. Beyond such insights also lies the unease motivating this author regarding the understanding of the nature of ship design by the broader stakeholders (Andrews, 2022). That is to say that few of the other players in the ship design process seem to comprehend the unique nature of ship design. In part this may be due to the vast bulk of ship design (especially in the commercial field of transportation vessels – see the distinction made in Section 2.1) just following a basic evolutionary or even a "type ship" based approach. However, it could be argued that not just "service vessels" but ships in general will have to be designed in a more questioning and responsive manner to cope with the likely complexity of the future "market" and design environment (see also Section 4.3).

Thus, further design methodologic insights of a philosophical stance will arise beyond those brought to recent IMDC DM presentations, such as by Love (2000) (see Andrews et al., (2006) for discussion) and Nelson and Stolterman (2012) and even critiques of questionable views, such as those due to the philosopher Parsons (2016), who in his "philosophy of design" excludes engineering design entirely from consideration. Both of the last contrasting texts were reviewed in the IMDC 2018 DM report (Andrews and Erikstad, 2018) as it was considered discussing such different views serves to counter narrow understandings of design as well as to where ship design sits, both in wider engineering design practice (Andrews, 2010b) and with regard to similar design fields, such as architecture. This is not just due to the need to look to the human factors' component in ship designs and the nature of the ship design process, especially now AI developments are "around the corner", but also because the architecture of ships has parallels with (and clear distinctions from) the architectural design of "bespoke" buildings. Finally, it is worth mentioning, alongside the quantum physicist, Rovelli's (2018) defence of thinking philosophically (see Andrews 2022), an eminent design engineer, Ove Arup. Arup, interestingly went from studying philosophy to becoming the greatest structural engineer of the late 20th Century, in complete contrast to Ludwig Wittgenstein's opposite journey (Sterrett, 2006)), thus Arup wrote strongly about his philosophy of (engineering) design (Arup et al., 2012) which he saw as holistic.

3.2 Ship design issues

In their excellent IMDC 2022 Design Methodology State of Art report, Erikstad and Lagemann considered there to be four "evolutionary tracks" typifying strategic approaches to characterise the "high level plan(s)" that are adopted to organise the ship design process. Despite also criticising the ship design spiral's limitations (as in Section 2.3 above) they see it as the origin of the four tracks: model-based systems engineering; set-based strategy; configuration-based approach; and an optimisation strategy. One or more of these tracts were used by them to identify the design strategy used by each of 34 PhDs produced in 2016 to 2022 from the 10 universities, which can be said to be the centres of academic research in "marine systems design".

As the originator (Andrews, 1981, 1984) of the "configuration based" (or inside-out/architectural) approach to ship synthesis, I would question whether these four "tracks" are all comparable as approaches to ship design or even strategic in the same sense. The difficulty as I see it is that (as Erikstad and Lagemann acknowledge) there cannot be a "one-size-fits-all" model of ship design (Andrews, 2018a) and the four "tracks" together don't necessarily address the same level of ship design process. Rather than the configuration-based approach being "strategic", I see it as a more sophisticated approach to ship synthesis (than just a simple numeric balance sometimes called "point-based design (Singer et al., 2009)) that can be chosen instead of a purely numeric (weight and space balance) or even a fixed sequential one (as implied in the design spiral). This is particularly appropriate to "complex and novel mono and multihull forms" (including naval submarines and configuration driven surface vessels), especially where the internal configuration is complex and actually drives the sizing of the vessel (see Sections 6.1 and 8.1 to 8.4 of Andrews (2018a)).

Is also worth, when considering possible ship design "tracks", comparing both Andrews seven types of ship design for increasing design novelty (Andrews, (2018a) Table 3 and Section 5) with Papanikolaou's (1997) four types of "fundamental initial ship sizing methods" or ship synthesis: -

- The parent ship "by interpolation but un-innovative" i.e., "type ship";

- Regression data “averaging empirical values for specific ship types” i.e., akin to design lanes and “evolutionary design”;
- Density approach “empirical coefficients – “crude” formulae for payload fraction, vessel density and weight coefficients” i.e., akin to a numeric synthesis (item 4 of Andrews (2018a) Table 3) built into student design exercises and many spread sheet approaches (Hyde and Andrews, 1992);
- Parametric variation “first principles “versatile” CASD algorithms for innovative designs”.

However, I would argue that for true innovative design outcomes, just varying hullform coefficients and dimension parameters (even with CASD driven algorithms) without being combined with an inside-out (DBB) approach (Item 5 of Table 5 in Andrews (2018a)) results in a configuration, constrained by possibly inappropriate choices and, even, by algorithms (invisible to the CASD user), that is hard to layout and hard to work up to meet modern multi-dimensional design aims and constraints.

The strategic track appropriate to such “configuration-based synthesis” can draw on system-based, or optimisation techniques and even set-based design process strategies. However, I prefer a higher-level strategic approach to (complex) ship design, by which I mean the concept designer should follow a clear decision-making strategy, that is knowingly making significant choices about each of several design options, rather than all too often “just doing what we did last time”. I have simplified this strategic decision-making process for a single design option – in a wider solution space (see Figure 4 of Andrews (2018a), with each step spelt out in that paper’s Appendix A and reproduced here as Figure 1). A version, appropriate to tackling multiple design options, using the decision-making overview/strategy is given by the “rich picture” representation (with, in that case, showing just four concept options) by Andrews and Andrews (2021), which was reproduced as Figure 13 at the end of the 2022 DM SoA Report (Erikstad and Lagemann, 2022) and also is here as Figure 2, presented at the end of Section 4.

There could be said to be related ship design issues associated with one other of Erikstad and Lagemann (2022) design methodological “strategic tracks” – that which comes under the umbrella of “optimisation”. While this can be seen as a design strategy appropriate to the marine sector, as it is for example the basis for Papanikalou (2022) EU HOLISHIP project, optimisation has also proved attractive at a ship sub-system design level, particularly applied to structural weight minimisation. To me, the latter is seen as a common error often used in much of engineering analysis, where optimisation poses as a design approach, thereby exhibiting the flaw that “we have a good technique” (meaning highly mathematically amenable) “so let’s use it here”. This is too often done and called “optimisation” or an optimised solution, when at best (in whole ship terms – or even more so regarding a whole maritime transportation system) it is minimising a sub-system (say, steel weight). As such it is a classic version of sub-optimisation of the intent of the ship or worse the fleet or wider business system.

The argument for optimisation can have even worst implications if applied to designing service vessels, where both the wider system is likely to be ill-defined and, often, the ship’s purpose is to deal with the unexpected (e.g., Offshore Support Vessels (OSVs) or naval vessels – see the discussion on what is a “good (ship) design” in Andrews (2022) and summarised in Section 4.3 below, where both Brown’s (2000) analysis of the performance of the British Navy ship designs in World War II is covered and the quite different approach to designing OSVs by Ulstein and Brett (2015). In fact, these two cases can both be seen to be facing up to the subtilties that most optimisation approaches don’t properly address. I think it would be of concern if AI/ML enhanced ship design was to go down a “black box optimisation” path rather than be used to help address the key decisions flagged up by Figure 4 and the associated exposition in Andrews (2018a), which Figure 1 summarises.

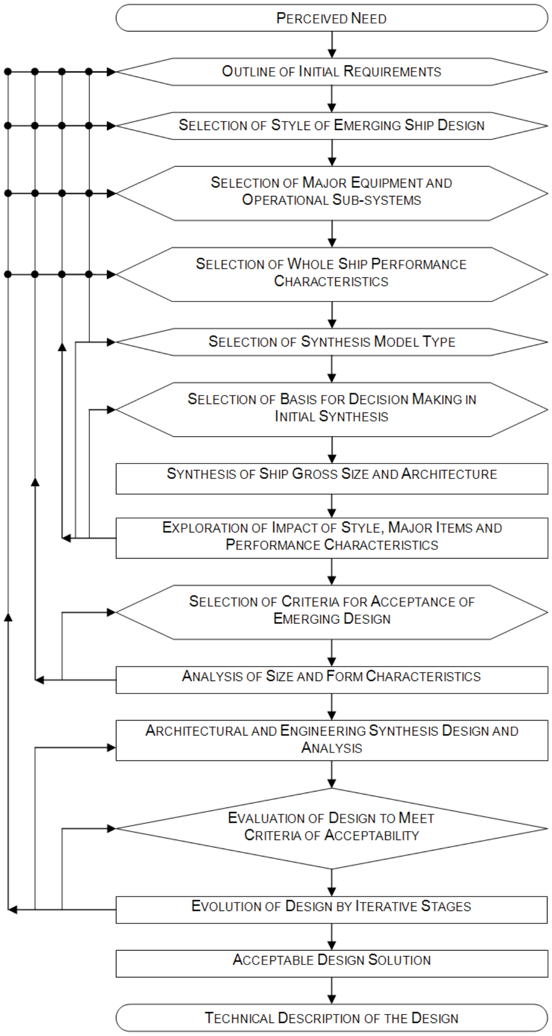

Figure 1: A Representation of the Overall Design Process for PL&C Systems Emphasising Key Decisions (see Andrews (2018a) including its Appendix A that describes each step, in detail)

3.3 Ship Design is Decision-making

Although the characteristic that is seen to typify ship design – that of making major or key decision(s) has already been highlighted (and emphasised in my key publications, including IMDC design methodology SoA reports) this section specifically addresses this. This is because this was seen as the key message of the 2018 Special Edition (Andrews 2018a), where the heart of the message of that extensive publication is at its Section 3. This section, which was entitled "The fact that the concept phase is unlike the rest of design", can be summarised: -

1. There are many views of early stage/concept phase ship design: This suggests that each study is different and searching for a set approach (even for different options of the same concept) in a concept process is questionable?
2. For the design of physically large and complex (PL&C) systems the design practice of wider engineering and other sophisticated design fields (like architecture) provide insights but also raise distinct issues of their own.
3. The concept phase is different to the subsequent phases of design – as it is about big decision-making: While all design involves making decisions (see Ferguson's (1992) "dozens of small decisions and hundreds of tiny one's"), those, often made by default or without question, in the Concept Phase are almost always the most important and hard to go back on beyond that phase.
4. Different (ship) design processes are distinguished by the nature of each potential option's novelty as shown by the table of increasing novelty (Andrews (2018a) Table 3) where each type is spelt out in that paper's Section 5.
5. The motivation for the concept phase is to undertake Requirement Elucidation (because of the nature of the design issue is that it is a "wicked problem" (see Rittel & Webber (1973) and full comparison of this urban design term with ship design practice is in Appendix B of Andrews (2018a). Again, it is necessary here to point out the term "wicked"

does not mean such design is complex, but rather the "wickedness" lies in determining what is actually the objective or set of balanced objectives that the new design is intended to meet through a Requirements Elucidation activity.

6. Why the concept phase (particularly for complex vessels) has a different design motivation/objective to all subsequent phases, which are focused on working up a chosen and initially balanced ship design to construct, assemble, set to work, operate, maintain, and to be disposed. So, the concept phase does not have the same design focus but rather a meta-design stance, that leads post-concept to what many seem to see (falsely) as "design proper" i.e., engineering analysis of the progressively worked up solution and build description.

The above list, apart from reinforcing the 2018 paper's assertion of the sophistication of ESSD for (certainly) complex vessels, also should have demonstrated that the design spiral is a simplistic and inaccurate summary of such sophistication and is no more than a reminder (sort of) of the iterative nature of much of design, which is used to achieve and maintain ship design balance. But, with the expanding scope of design tools and methods, not to mention CASD's ability (already the case before further AI advances) to inform the sophistication spelt out in the summary above, leaves both CASD developers and users with the responsibility to question those design decisions. These range from the strategical to the myriad (see Ferguson, 1992) and their potential impact on each design option being explored. The range of options covers both those being further pursued and those, perhaps, rejected with insufficient further consideration. The latter approach remains all too common a procedure, due to the pressure to "get through concept" and "get commitment" to work up the (crudely in design exploration terms) chosen concept design, which is then taken into feasibility and subsequent detailed design and build.

The author, in several of the examples of his "real" (as opposed academic) design projects (see Table A1 for top level summaries of each project's distinct design drivers, constraints and outcomes), was forced to revisit the chosen and developing concept-based design, not just in the subsequent feasibility phase but very late in the contractual phase or even in detailed design. Sometimes this was due to a design "flaw" emerging, but more often it was due to "the need to reduce initial build cost" (below that best costed in concept design) or to cases of late major changes that the "end customer" declared were "more important to incorporate than keeping the ship (usually the first of class, sometimes seen as a sort of prototype) to the contracted programme and cost". This might not often occur outside the very resource intense and politically charged (meaning politics in both senses) naval "ship" procurement environment, but I would hazard that when this does occur elsewhere this is due to commercial pressures to proceed to build, despite it often being obvious that a "better" design could have been worked up with emerging hindsight?

I have already criticised use of the design spiral and, given the theme of this paper that the scope of the ship design process is ever expanding, this critique also relates to an all-too-common view that design is merely "working up the specification". To some extent this is the approach in architecture and civil engineering for complex "one-offs" – once an architect's concept has been selected (after, say, an architectural competition). Of course, the question is "who writes the spec?". I would argue much that is covered in the outline of a sophisticated concept phase in the six points in the first paragraph of this sub-section (summarising Section 3 of Andrews (2018a)) needs to be well addressed and should underpin any coherent specification. This would still be the case even if the decision is to select an "as previous/type ship" option, if that has been coherently arrived at through proper Requirements Elucidation (Andrews, 2011).

Certainly, any properly evolved concept phase should follow the process undertaken for most service type vessels and, I hazard to guess, that in the uncertain future for the design environment in which many more commercial ships may emerge, that their acquisition is likely to be more exposed to such decision-making implied by my six points above. I would contrast the exposition in Andrews (2018a) to that of, say, Watson's (1998) detailed and informative "practical ship design" text. Watson's exposition of commencing ship design with a detailed specification and then working up a clear (specification detailed) concept, is contrasted with commencing much earlier in the design process with a true *ab initio* ship design, as called for and outlined in Andrews (2018a). So, the former will more likely end up with an incoherent concept than one following Andrews (2018a) outline. This is discussed further in the next main section addressing the changing nature of the objectives in ship design practice.

3.4 The Ship Design Process is a human endeavour

As the design tools and data driven design (D3) becomes ever more capable, what remains then of the role of the human designer? This begs the question that we can define a measure of design system capability, when for many designs we cannot define an adequate measure of performance in comparing each design solution, particularly through its life in an uncertain future. If we believe that designing a PL&C system, such as a complex vessel, remains a human driven process then how do we ensure that control and decision making is not subsumed by ML/AI capabilities that are likely to come on stream, as is considered in Section 5?

It is a fundamental belief that a properly sophisticated approach to ship design (especially in ESSD) for complex vessels, requires full human engagement, such that using CAD systems as assistance to the designer, can be followed through despite more advanced methods increasingly drawing on the data mining and analysis of what is called Artificial Intelligence. The description of the ship design process I favour is one that is a series of high-level decisions addressing the basis behind that design process with as wide a sense of the full practice being undertaken. This must cover exploring widely, not just the solution space but questioning the sequence of design investigations and the basis for design decision making (see Figure 1). It must also question, or at least acknowledge, that any design approach is biased by the design education and experience of the ship design team, the methods, tools and data they choose (or are constrained to use) to adopt on each design study, or possibly each individual design option, they select to populate the solution space. This selection should be motivated by being part of a Requirements Elucidation (RE) philosophy (Andrews, 2003b, 2011) and should lead to insights into each particular design's main design driver or drivers, which then focus the subsequent design evolution.

This RE approach includes the major decision for each significant option of the style of that design leading to the appropriate design synthesis type dependant on the novelty of each option, as is spelt out in Section 5 (and Table 4) of Andrews (2018a). That this can be seen as a very human process has been humorously captured by the 'Rich Picture" by Andrews and Andrews (2021) of the naval SDP example in Figure 2. This human endeavour is further emphasised by the need for the ship design naval architect/ship design manager to lead the decision-making, that only they (or in a worst-case practice, the CASD synthesis system/creator) can holistically direct in arriving at a balanced concept design and a coherent set of requirements to take forward through the requirements elucidation dialogue. This ought to involve all the necessary stakeholders – but more likely just the ship owner or requirements owner. Relevant to this is the insight of those software engineers that based their systems approach, known as Systems Architecture (Maier, 1998), on what they perceived was the creative, balanced and integrative approach to the whole design, from initiation through to acceptance (and even in-service), by the "first systems architects", that Maier calls naval architects (see Andrews, 2015).

The exercise of this "system architecting" to maintain the coherence of the original concept design has been seen in major defence projects as the task of that project's named individual chief engineer, acting as "the Design Authority". (See Gates (2005) for argument for the UK Type 45 Destroyer contracted project exercising Design Authority and Betts (2006) and Andrews (2006b) arguments against that case study's viability.) This further shows the very "fuzzy' nature of the endeavour of designing and procuring such complex vessels. In reality, that endeavour is achieved by an initially small group of individuals, but for most of the design process, then undertaken by a large number of detailed designers in discrete (contracted) teams, hopefully united by the project intent. This is a social and human endeavour, with all the psychological complexities of such activities, hinted at in Figure 2 and reflected in histories, such as Hughes (1998) for four major US technological projects and Johnstone-Bryden (2018), on the origins of the UK Post-Falklands War's Amphibious Replacement Fleet. In the latter case, Johnstone-Bryden records the current author's pivotal early role in ensuring the project for the new assault ships survived its early progress against "administrative animosity".

3.5 Conclusion on Ship Design & the Ship Design Process

In spelling out the nature of ship design and the process at the most complex levels it is practiced, I now argue that this also means (given the theme of this article) that the task of better understanding what a new ship design is intended to achieve and how all those involved might best be engaged, needs to be debated. Another aspect of the expanding scope of this practice is the extent of those involved, namely, intended users (i.e., sailors); owners (be that government or shipping operators); the other disciplines, beyond our focus on the whole ship designers; the wider set of stakeholders, which goes beyond the shipbuilder and a host of systems and equipment vendors to include commercial, insurance, classification and consultancy sectors and, often, wider society and if things "go wrong" both public and media involvement (see Yule & Woolner, (2008) on the Australian Collins Class Submarines).

The other immediate conclusion is that this involvement of a growing set of organisations, is changing the process. This then suggests that any consideration of ship design and the SDP must recognise the need for multiple levels and types of dialogue, especially in the crucial earliest stages in the most sensitive ship programmes. I have long argued that any such dialogues are better facilitated by architecturally based descriptions or sketches of potential design solutions. This is part of seeing the concept phase as drawing on the right set of tools, given the object in the concept phase is not doing better "classical naval architecture" (i.e., S^4) but undertaking: -

- a better exploration of the solution space (see Figure 8 of Andrews (2018a));
- questioning requirement assumptions in the light of design implications;
- and (initially) searching for unknown synergies (such as a Trimaran combatant solution being better at facilitating enhanced organic aviation assets with less total ship impact than a monohulled "equivalent").

This need for wider exploration at concept led the author to question CASD tools that "provide faster concept design" (de Winter, 2018). I said this because "faster concept design' would be at the price of coming out of the concept phase with apparent insights that appear to give solutions with "better naval architectural definition" but lacking a robust exploration of the solution space and of a demonstrated coherence between design and requirement (Andrews, 2019).

4. SEEING THE OBJECTIVES IN SHIP DESIGN AS HOLISTIC

4.1 The Issue of Human Factors in Ship Design

The traditional view of what is wanted in exploring the role(s)/ performance/cost of even the most complex service vessels, such as naval combatants, has emphasised the operational needs in terms of incorporating into the design equipment (e.g., weapons/sensors/command and control (for a combatant) or towing capacity/manoeuvrability (for an Offshore Support Vessel)) or providing facilities onboard (e.g., a flight deck and organic hangar (combatant) or stowage of rig supplies or spare wind turbine blades (OSV)). However, this leaves out consideration one significant aspect of the total "system of systems" (Andrews, 2022) that can be said to constitute a complex vessel, which is that of adequately integrating into the ship design the personnel onboard. This is a challenge as the personnel, who work the vessel, also live on the completely constructed and mobile environment, which is something that is not replicated in the designing of onshore architecture or urban constructions.

Despite the fact that RINA, as the major international institution for the profession that leads ship design, has for several decades held specific conferences to address 'Human Factors' (or ergonomics) in regard to ship operations and hence ship design (RINA, 2023a), little progress seems to have been made in putting this key aspect of the "system of systems" into the design process as an integrated part of designing ships. When the contents of such regular HF conferences are inspected, one finds many papers by ergonomists, that are relevant to ship design, bemoaning the fact that their emphasis on a scientific approach to designing ships so the crew can work onboard efficiently and also live for long periods on the vessels which are effectively their homes, is poorly considered in the ship design process (Cook, 2017; Schumacher and Banks, 2019). The reasons for this, like much of how ship design has been taught to naval architects and practiced in detailed design (where ergonomic relevant issues have largely been addressed, if at all), usually in the shipyard drawing offices, lie in the origins of modern ship design and procurement practice. When ships are compared with (say) aircraft, the maritime approach has been one of "cheap and quick" initial design combined with the highly significant absence of prototypes or extensive production runs, in favour "bespoke acquisition". This has led, since the beginning of time, to nearly all ship owners to both directly influence "their" ship's design and any consideration of ergonomics in it. Thus that consideration has been regarded as secondary by all involved except engaged Human Factors experts and those directly concerned with the welfare of the sailors onboard.

I was asked by the UK Nautical Institute, as the professional institution for mariners, to contribute to their most recent publication entitled "Improving Ship Operational Design" (The Nautical Institute, 2015), which was said to be primarily addressed to the naval architect "to improve your design". Thus, I spoke for the ship designer in two introductory sections: on the evolution of a ship design through to its final design (using a naval vessel as a very complex case study with high density of personnel onboard); and on the general (ship) design process, including the role of the naval architect. So, I sought to disabuse the HF experts as to why ship designs largely fail to be ergonomically designed. There are of course exceptions, particularly modern ship bridges and machinery control rooms in most ships and high intensity combat compartments (such as the Operations Room/Combat Information Center (CIC)) in naval vessels. However, the vast bulk of the spaces in a ship inboard (such as the key main passageways) and on most of the upper weather decks, where physically demanding operations are largely carried out, are not subjected to intense ergonomically driven design. This is because the scale of the product, the lack of a full-scale prototype (to iron out poor ergonomic design), and the manner in which shipyards win contracts (by the lowest price bid). Thus, at the level of detailed design, the focus is primarily on production aspects to meet contracted cost and time. So it must be admitted (as my section in the Nautical Institute 2015 publication tried to explain to the disappointed HF experts), detailed ergonomic concerns come low down in priority when compared to those aspects that have dominated ship design, which remain the naval architects' primary concerns. The latter have to ensure the ship design (as agreed at the end of the concept phase/bid acceptance) remains balanced and stable, structurally intact, achieves contracted power/speed/endurance, and (maybe) is appropriately seaworthy. So traditionally, any detailed ergonomically good features are addressed by the detailed designers with appropriate inspections, but only if "an expensive" acquisition process has been contracted. Otherwise, anything more than "usual practice" is unlikely and also to be low on the naval architects' priorities, needless to say, this has been (rightly) ill received by HF experts.

If we assume both greater levels of automation in future vessels and fewer highly trained personnel at sea, then perhaps (outside exceptions, such as the US Navy's Zumwalt Class combatants with extensive automation to reduce ship's complement (Feege, and Truver, 2016)) more attention ought to be paid to HF, as yet another sub-discipline for the naval architect to master. This was the question I posed at the 2018 IMDC: "Does the future ship designer need to be a human factors expert?" (Andrews, 2018c). There is some useful guidance (beyond the papers in the RINA HF conferences already mentioned) by authorities such as Sherwood-Jones (2005) and Cook (2017) as well as the contributions from several authors in the Nautical Institute (2015) publication. One can even look at urban design, where terrestrial architects have long given attention (at least in the best designed buildings) to the needs of their human occupants. A comprehensive example of this was summarised in my (2018c) paper, namely Broadbent's (1988) seminal text which "places (the role of) the psychological and cultural aspects" at the centre of building design. Thus some 21 human sciences (from Anatomy to Sociology) are outlined for architects, some of which Broadbent considered provide useful information to designers. While it might be argued (as indeed I largely did in Andrews (2018c)) that there is little scope in a naval architect's current education for acquiring in-depth ergonomic skills, some might see AI as about to readily "assist" by performing much of the naval architect's traditional "engineering" computational role. This could then leave room for more creative and "human centred design" capabilities? Once more, the author's emphasis on a graphically and architecturally centred "inside-out" ship synthesis approach (Andrews, 2018a) provides the scope to foster a holistic HF consideration more readily, right from the initiation of any ship design study.

4.2 Broadening the set of Ship Design Objectives

Beyond the likely increased scope in ship design for HF aspects, there have already been quite a few approaches over recent decades to essentially broaden what has been traditionally seen as ship design objectives. This broadening can be seen as a wider mix of specific objectives, in terms of improving performance against cost. Defence procurement organisations in democracies, where the underlying objective can be seen to be achieving the best capability or set of performance characteristics for an acceptable impact on the defence or national budget, might be considered a basis for making procurement decisions for specific major (naval vessel) programmes. However actual practice is far from that straight-forward and is probably an explanation as to why major naval acquisitions are so politically sensitive. Thus, the placement of orders for individual vessels for a nation that has several comparable shipyards (a diminishing situation for even major naval powers) can result in the allocation of a batch of vessels between several yards for political reasons, despite usually being economically less efficient. Or a major feature in a design can be imposed to sustain a specific national industrial capability. (A clear example of this was the French Government's insistence that the CHARLES DE GAULLE aircraft carrier be fitted with two nuclear power plant to maintain that production line for the French Navy's nuclear submarine fleet. Such pragmatism, beyond the individual procurement of that vessel, also occurred when the build duration of the same vessel was deliberately stretched because the government facility, in which it was built (Brest naval yard), did not increase the workforce but "built more slowly" to keep continuity of labour force demand. This meant that individual programme's total procurement cost was greater but the "cost" to the national budget was more efficient year on year and the wider national naval shipbuilding capacity (in continuous build and constant workforce) better maintained.)

That wholistic French approach, outlined in the above paragraph, can be contrasted with somewhat parallel UK programmes in which I have been involved, where a project "silo mentality" of just considering "your project", was demanded of individual ship projects at the risk to a coherent national industrial capability. Such examples justify my view that the constraints on such sensitive national programmes need to be recognised for their potential impact on key early design decisions (see Figure 3 and Table 2 in Andrews (2018a) for further discussion on the importance of the three types of constraints on the ship design process). So, while there can be sophisticated ways of compounding a set of detailed objectives for a new design (such as multi-criteria approaches (see IMDC DM reports Andrews et al., 1997, and Andrews et al., 2006), cost effective presentations (see Hockberger's (1993) critique) and Pareto Front presentations (see Purton, 2015 and Burger and Horner, 2011)), such methods are best used to provide insights, reveal broad trends and to be seen as advisory, rather than obeyed without question when making design choices (Andrews, 2021a).

A non-naval and government driven practice, that faces up to the broadening scope of assessing the basis for judging the right mix of capabilities to achieve the best design choices for multi-role service vessels in an unpredictable market, has been produced by the research of Gaspar (2013) and the associated investigations reported by Ulstein and Brett to the 2015 IMDC. Both Gaspar's adoption of the M.I.T. Epoch Era approach and Ulstein and Brett's (2015) division of the aspects that a complex vessel design needs to address, have been proposed in preference to simplistic summing of performance metrics weighted against build or, even, predicted through life costings, which are inevitably high risk. Thus, the latter authors' three elements of ship design objectives consist : -

1. Design for Efficiency: namely, Technical (over the design's life cycle); Operational (for different missions); and Commercial (systems influencing valuation, preferences and exploitation regarding Return On Investment (ROI);
2. Design for Effectiveness: namely, Safer, Smarter, Greener;
3. Design for Efficacy: namely, Flexibility, Robustness, Agility.

In many respect one can see this more comprehensive basis for assessing a "better ship design", as comparable to the current author's separation of the purely technical (historic ship design) issues, summarised by "S^4" (Brown and Andrews, 1980) from the more holistic issues under the 5th term "Style". (See Table 1 in Andrews (2018a) for the case of a naval combatant, Table 1 in Andrews, (2021a) for the "Style" items of a submarine and Table 1 in Andrews (2018d), comparing Style issues for a combatant with the Style breakdown for an Offshore Support Vessel, the latter being a comparable example with Ulstein and Brett's typical shipyard products.)

Many of the "qualities/issues/capabilities" identified in Ulstein and Brett's (2015) Design for Efficacy also occur in Andrews (2018a, 2021a, 2018d) style tables. Thus, Flexibility in a design is a measure of being adaptable to new conditions, and hence the Style term Adaptability (see also Andrews, 2001) is comparable – in fact I prefer the latter term as from a structural design stance I don't want excessively flexible ship structures. Robustness is identified by Ulstein and Brett as being better able to resist failure modes or to accommodate changes in operating contexts and is repeated in my Design Style listing. (A classic example of responding to experience was the case of a "highly efficient" modern structural design found wanting when in the UK-Iceland "Cod Wars" in the 1970s, very expensive British frigates were damaged by "robust" Icelandic gunboats. Thus, the next class of UK frigates were specifically structurally beefed-up around their bows.) Agility was defined for a design as being more readily modified through life, whereas the Design Style listing assumed this was part of a wider definition of Adaptability. Achieving the latter often comes down to providing adequate (weight, space, and stability) margins, beyond the design margins. The latter reflect the designers' need to provide sufficient allowances from the start of a design through to its completion to accommodate design uncertainties, in a manner that these margins are progressively absorbed in the budgets up to completion (Gale, 1975). The margins provided for mission changes and significant equipment additions through life are often excluded, against the ship designers' advice, in attempts to "keep the design tight". An example of this is the UK Type 42 Destroyers discussed in the next section.

4.3 What is Good Design?

It could be seen, for such complex service vessels as those focused upon above, that this clear broadening of scope in current ship design practice, is just making ever more demanding that complex decision process (such as that seen strategically by the author's main SDP representation, which has been provided in many papers - see Figure 1). Another way of looking at this is to take Ulstein and Brett's (2015) paper's title question and see it in terms of identifying what is a "Good" design. This I see best done through the design of naval vessels, the justification being that (as Table A1 shows) these are many and varied, both in their several sub-types (e.g., combatants; amphibious vessels and craft; submarines and auxiliaries and even a royal yacht) and their different ship configurations, from Trimarans to nominally "commercial/utility" styled warships.

One way to investigate the nature of good design is to draw comparisons between broadly similar completed ships produced in a similar timescale. This was done by Brown and Andrews (1980) for a set of British warships produced over the last century. These five pairs of design comparisons were each of a "first-rate" design compared to one deliberately "second-rate", in terms of comparable capability, the apparent logic being that more cheaper hulls could then be afforded. In every comparison the (relatively) marginal extra procurement cost for the "first-rate" was found to be better value for money, both in added performance and in longevity of service, the latter being seen as a measure of successful design. Specific design comparisons have been discussed in earlier papers (Andrews, 2022 and 2017b) thus the UK Type 42 (Air Defence) Destroyers have been compared to the "first-rate" Type 22 (Anti-Submarine) Frigates produced shortly after. The T42 was a tightly packed design to reduce procurement build cost, but this meant necessary up-grades through life of that class of ship became a very expensive exercise, leaving the ships' overall performance significantly degraded. In contrast the T22s, having been designed with decent design and future up-grade margins, which initially led to accusations by operators that they were inadequately "armed", were both more easily maintained through life and the design easily "stretched" twice to produce very successful further batches of the class. This suggests that if a more holistic approach to design choices had been adopted the British Navy might have lessened the shrinkage of its fleet, even before the end of the Cold War and the subsequent (premature) taking of a "peace-dividend". The second example is of the UK and US comparable submarine designs, which revealed an interesting holistic insight into submarine design. Thus, the case of the UK SWIFTSURE Class when compared with the US THRESHER/LOS ANGELES Classes, as is debated in Andrews (2017b), where it was questioned as to whether the latter seemed to have been "sub-optimised" for high top speed rather than the more resilient and noise reduction configured SWIFTSUREs and their second batch TRAFALGAR Class?

Considering the good naval vessels design debate above, alongside the offshore support vessels that were the focus of Ulstein and Brett (2015), then the clearest naval ship design analysis was by the naval ship designer and technical historian, David Brown (2000), who went back to the last extensive wartime example, that of WWII. Andrews (2022) summarises Brown's analysis which concluded the (British) fleet's overall design performance was "probably the best that was achievable within the UK's marine industries capability to deliver". Brown remarks that the best design according to "some naval architects *(is the design)* that meets the *(formal)* requirement at a reasonable price" but Brown disputed that, as being far too narrow a definition. He proposed a better definition lay in that by the 1842 UK Parliamentary Committee on naval ship design which ends: "...to endeavour to produce the best effects with given means". Thus, the basis of what is "good design" is consistent with the "Fleet" arguments in the following sub-section and sensibly leaves the issue qualitative and reflects my belief that ship design remains a subtle and sophisticated multi-facetted and, therefore, human directed process.

4.4 Properly incorporating Readiness/Sustainability/Availability

One of the measures of a good design achieved by focusing on "design style" issues (see in the last column of Table 1 of Andrews (2018a)) would be a better recognition that the process is one of designing several complex vessels, which usually consist of a class design providing a "fleet capability". This might be for a naval force or providing support to the growing number of large-scale offshore facilities (i.e., by OSVs), and therefore to move away from a traditional "good design" approach focused on an individual ship. Rather, the measure in such cases should be directly focused on a significant number (say six hulls) of units and their total fleet availability. This focus has only recently achieved prominence in the open organs for discussing naval ship design, such as the RINA annual "Warships Conferences". At the latest of these devoted to submarine design, Availability was headlined (RINA, 2023b).

The reason for this emphasis on availability could be said to have arisen due to the extensive press coverage in Australia and the publication by the Australian Government of several reports on the very poor operational availability of their six COLLINS Class conventional submarines (Coles, 2012). This then led to the topic for the 2023 RINA Submarine conference (RINA, 2023b), namely "Capability and Availability in Submarine Design". I took that title and turned it into a question (Andrews, 2023) and concluded, from reviewing some four decades of papers on submarine design in such conferences, that most submarine design presentations have been on how the design of these unique vessels is different to that of the most complex surface ships. Thus Andrews (2017b) is entitled "Submarine Design is not Ship Design" and like many of those papers is on the design of both non-nuclear and nuclear-powered submarines (the latter being the most important and costly distinction in submarine capability and design), and it does so largely in terms of the design of an individual vessel. Whereas, Coles and his team in investigating for the Australian Government why their "current level of availability ..*is*…poor" (both absolutely and relatively to comparable submarine fleets), provided some five main issues and 25 recommendations to achieve better fleet availability than those of comparable forces. Most of these identified improvements came down, not to the direct submarine design aspects but the wider management by three sets of participants:-

- "At a national level combining the main government responsibilities (such as funding and overall ownership authority);
- The Australian Navy and wider Defence organisation.
- The related submarine industry, especially the designer and builder (the Australian Submarine Corporation)."

Andrews (2023) saw this expanded scope of "submarine design", which ought to focus on sustainability/availability/readiness of a whole class/fleet to achieve through life performance for the number of "available hulls" to the Fleet Commander, to be a paradigm shift (to use Kuhn's (1962) term for scientific revolutions) in the design of such complex products. This clearly is a major expansion of the way in which design of such complex vessels is addressed, namely, by focusing on designing such vessels and seeing the capability sought from a class/fleet perspective, rather than just producing a good technical solution for a single vessel. Thus, the traditional approach has the danger of failing to give sufficient attention to through life (TL) availability of the whole enterprise. So, it is necessary to design for "support" from the start and, once again, an "inside-out" synthesis can best encourage this from the concept phase.

The above term, enterprise, was adopted in recent conference paper by Macdonald and Nicholl (2022) entitled "Nuclear Submarines – the most complex endeavour in defence" and directly addresses the Australian intent to acquire a fleet of SSNs, with the active involvement of the USA and UK. These authors argue, from their experience as senior UK MoD engineers and in subsequent leading roles in the naval acquisition industry, that the wider aspects are what make the design and acquisition and through life (TL) ownership of nuclear submarines such a demanding and unique activity. This complexity is seen to be the joint involvement of players from: industry; finance; military; societal; legal and regulatory; and political, and they highlight 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, acquiring such a broader whole system understanding from those involved in submarine design also requires this national commitment. Thus, as a designer, teacher and researcher in submarine design and bearing in mind the insights from the analysis in my 2023 paper that the key capability of Fleet availability needs greater prominence, I consider Macdonald and Nicholl's paper should also have had a greater emphasis on the unique demands required of submarine designers when designing such a demanding system of systems. Given specifically, that military submarines have to operate for extensive periods in extreme physical environments, this requires submarine designers, in addition to all that "normal" naval ship designers need to appreciate, to further understand two unique sub-specialisms regarding the physics of these large and relatively fast vehicles, that are not necessarily obvious from the wider ship S^4 issues (see Section 3.1 Item 4 above): -

- the physics of pressure hull collapse (see Faulkner, (1983) for an overview and key references), and,
- manoeuvring at speed in three dimensions, which is more akin to modelling aircraft behaviour than that of a ship (see Chapter 8 of Burcher and Rydill (1994)).

I have taught both these subjects, at master's level, from first principles. When this extra understanding is added to general naval architectural principles and the skill of integrating the many sub-systems (from nuclear power plant through combat systems to the many fluid service systems in a densely packed and finely balanced vehicle of several thousands of tonnes (see Mukti, 2022), which is also home to some hundred or so highly trained sailors, then this truly can be seen as a pinnacle of engineering design. This specifically requires producing and sustaining an engineering cadre, with that submarine naval architectural knowledge and experience, if this "indefinite" endeavour is to be successfully pursued at a national defence level of capability. So at least for the most complex of maritime vessels, the scope of "ship design" practice now has been recognised as a further expansion of ship design endeavour. Furthermore, this expansion might become more of the norm for general ship design practice, given the growing complexity to be expected of future of maritime endeavours plus the added question of what this might mean in an AI impacted future, which is explored in the next main section.

4.5 Incorporating a Better Systems Awareness

Given that a systems approach was the fourth of Erikstad and Lagemann's (2022) strategic tasks used to identify recent academic research in "marine design" when considering the broadening scope of ship design (see Section 3.2), it is sensible to consider both why a systems approach has been seen to be attractive in ship design practice and how that also has become a less purely technical management "philosophy" in recent years. Erichsen's systems approach has already been referred to in a formative approach to consideration of marine design. Alongside this consideration of the maritime transport "system", in Andrews (2022) I recently challenged the ship design applicability of systems engineering (S.E.) to an American (and largely naval) audience that has a long history of considering defence procurement as systems engineering and even synonymous with "naval ship design". Specifically, Andrews (2022) questioned whether, for complex ship design, S.E. is more of a management philosophy or even just a systematic procedure for managing such acquisition, rather than actually a method of ship design.

The latter question, regarding S.E. as ship design management practice, was argued in Andrews (2022), by referring back to van Griethuysen's (2000) IMDC paper and to an even earlier systematic rebuttal of S.E. as the solution to future ship design by Rydill (1978). The specific UK MoD obsession with the false "god" of Requirements Engineering was first rebutted in the 2003 IMDC (Andrews, 2003b – see also Andrews, 2011) by proposing a more open approach, namely that of design centred "Requirement Elucidation" (item 5 of Section 3.2) and drew on support provided by a strong argument against solution-less based Requirements Engineering by the systems engineering expert John (2000). Rather than repeat the argument for requirements elucidation, which I am pleased to observe is now common thinking, at least in marine design academia, I draw attention to my IMDC 2015 strong call for "Systems Architecture" (S.A.) as a better reflection of the systems philosophy. This has recently been further broadened and "softened" by ICOSE's new initiative (RAEng, 2021) under the banner of "Elegant Design" (see Andrews (2022) summary). This return to Checkland's (1981) "soft systems" approach can be said to better reflect the needs of managing a more complex world than the very technocratic "hard systems" vision of the past and seems a more general version of Ultstein and Brett's (2015) holistic design approach for OSVs. That S.A. also includes focusing on human factors, both from designing for people to be fully accommodated through making new systems for them and, separately, recognising the human nature of the design process (see Figure 2). It can also be seen to be more consistent with concerns regarding the engineering discipline's response to the potential impact of AI developments on future engineering design practice.

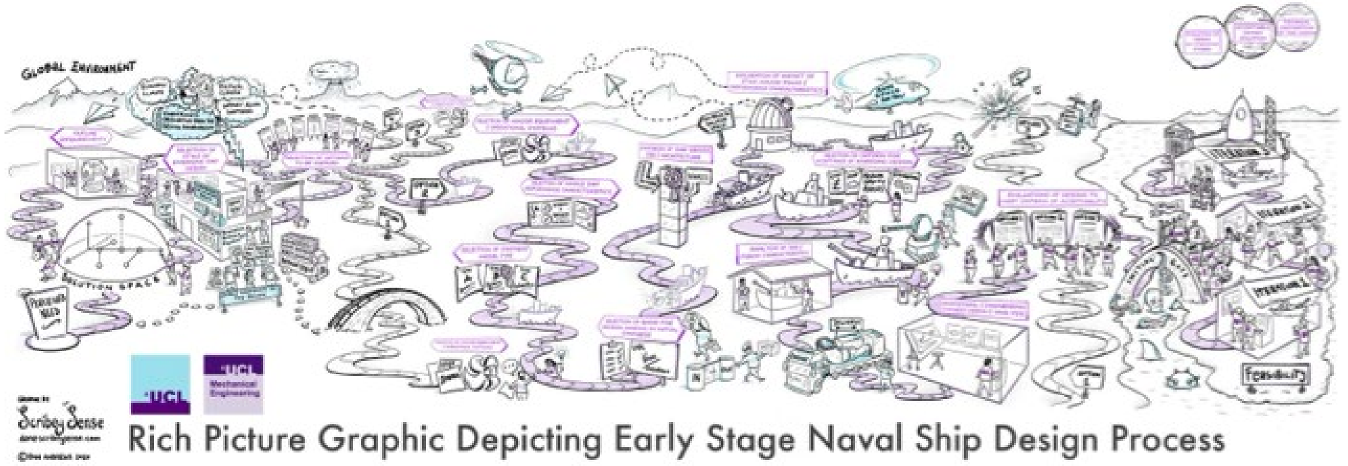

Figure 2: Rich Picture Graphic of a Typical Naval Ship Design Process (Andrews & Andrews 2021)

Finally, from a systems stance, which I consider to be a strategic management philosophy rather than a direct ship design approach, I remarked in Andrews (2022) that the US Navy, as the largest procurer of naval vessels, had concluded that it needed to take back control of ship design and construction, as a reflection of the complexity of such activities (Winter, 2008). This then had implications for how naval ship design is to be undertaken and how the engineers who will do this are educated and career managed (see also that this is one of the example significant constraints on how ships are designed, as listed in Table 2 of Andrews (2018a): “Specialisation and training of design team”). The best summary of how the US Navy’s ship designers are addressing this is given in the pithily entitled paper: "Ready to Design a Naval Ship? - Prove It!" (Keane et al., 2009), which presents three tables summarising the skill set and career experiences seen to be required by future Ship Design Managers. That this should be appropriately read across to all ship designers to meet the challenging future for ship design, I consider irrefutable.

5. THE FUTURE IMPACT OF AI ON MARINE DESIGN

5.1 Current state of art

While AI seems to be the current preoccupation for many involved in the design of technological products, it is not that design, since the advent of electronic computation and then CAD systems, has not been, with the continued existence of Moore’s Law, trying to cope with the changes to design practice that have been “assaulting” us for over half a century. It is worth tracking recent indications that suggest what might be the issues with the Machine Learning (ML) systems already upon us and furthermore how future AI developments will possibly impact on the more creative/human capabilities used to control complex design activities.

Data driven design (D3) was the response by Gaspar (2018) to my lengthy exposition on the sophistication of ESSD (Andrews 2018a), which the current paper on the expanding scope of ship design practice has heavily drawn upon. Thus, in Gaspar’s “technical paper” he proposes a D3 approach to “extract information and knowledge”, which sounds very like current ML proposals. He connects sophistication and complexity to Rowley’s (2007) identification of: data; information; knowledge; and wisdom (DIKW) and lists a common set of processes reflecting the description of the design of complex vessels (as outlined in Andrews (2018a)). He concludes with six key topics taken from Andrews (2018a), which Gaspar considers provides the challenge to implementing a D3 future: -

- “Quantifying Style;
- Comprehensive Synthesis;
- Success Factor for Ship Design;
- Design as a Learning Process;
- Aided versus Automatic;
- Architecturally Driven Data.”

All these issues and Gaspar’s related concerns, need to be seen alongside Bernstein’s (2022) ML analysis for urban architectural practice and Ruiz et al., (2023) similar view for the maritime industry, that are compared and contrasted in the next sub-section.

Before the ML comparison between urban and naval architecture is made, mention of Gaspar's (2023) paper on the "Past, Present and Future of CASD" is seen as pertinent. It is left to readers to go through Gaspar's excellent survey of the past and present and just briefly highlight his categories summarising the points relevant to the future of CASD: -

- "Hopes – problems that should be solved soon;
- Worries – problems that we may not solve;
- Fear – problems that we do not know that exist;
- Proposal for an optimistic future – A bias for data Driven Methods".

I am happy to note Gaspar calls for Andrews (2018a), as a comprehensive outline for ESSD, "to be implemented in design offices". This goes beyond the RINA Council's already unique commendation of Andrews (2018a) Special Edition publication as "a seminal paper, which sets the benchmark …considered to be essential reading for all naval architects and marine engineers, and not just those working in concept design." I would be delighted if this were so but six years on from the Special Edition (which includes the five eminent contributions to its discussion) being published in the RINA Transactions, I doubt it. Gaspar concludes by quoting my post-PhD paper to RINA (Andrews, 1986) with its call for "The more sophisticated design description *(from adopting the inside-out synthesis approach)* ... makes the designer consciously address, as early as possible, many of the less tangible design issues. …. to provide an open, responsive, and 'softer' approach to CAD", which ML and, hopefully, AI developments will also foster. But this will only be the case if the profession rises to this (ultimate?) challenge as a response to the ever-expanding scope of ship design practice?

5.2 Insights regarding Machine Learning from Architecture and Maritime Engineering

Phil Bernstein (a professor at the prestigious Yale School of Architecture and previously a Vice President at Autodesk) was asked by RIBA to write a book "about the implications of AI for the architecture profession", which he (interestingly) called "Machine Learning: Architecture in the Age of AI" (Bernstein, 2022). The book is comprehensive with many insightful diagrams summarising AI and architectural practice (seen as a business undertaken by the profession of architecture and by other stakeholders), rather than a detailed speculation on the actual design process. Thus, ML is seen as already involved in architectural practice, such that there are chapters under Part 2 (Relationships) that consider the "fuzzy parts" of architectural practice (in a manner akin to Andrews (2022) response to Keane's (2018) comments to Andrews (2018a) Special Edition's holistic but more design specific outline of ESSD). So, Bernstein covers economics and value/laws, policy and risk/professionalism/education, where he sees ML having a profound impact. Rather than try to summarise his detailed analysis, which includes comparing US and UK architectural processes and issues, I want to just pick out some pertinent comments in that book before turning to our own profession.

Bernstein opens with a professional strategy that recognises a "preponderance of intelligent machines in every dimension of design, construction and built asset operation" and then asks what then is the "proper role for humans". He quotes Daniel Susskind (2020) pointing out "computers are increasingly becoming capable of tasks as opposed to entire jobs" and then hopefully proposes "a more intelligent route" where "computers assist in the critical, but more mundane, aspects of practice: those that drive project delivery, technical precision and performative predictability" (Bernstein, 2022). All this sounds sensible and should be able to be read across to complex maritime "jobs". It also re-inforces my strong emphasis on managing the SDP though strategic decision-making (i.e., Figure 1's process which is informed by human intervention, as is indicated by cartoon like examples in Figure 2). There is much that is worth pondering in Bernstein's thoughtful and informed proposal, including an AI taxonomy to cut through a lot of popular hype and a pertinent question thrown up by the AI challenge, which he considers to be: "what is professional knowledge?" The latter question is also one to be addressed by any engineering discipline, such as those undertaking ship design and construction (through life).

Turning to a recent maritime article that also addresses the implications of ML, this is by three authors from ETSIN at the University Polytechnique of Madrid (Ruiz et al., 2023). One of the co-authors is Professor Perez Fernandez, who gave the 2023 RINA President's Lecture (Perez Fernandez, 2023) entitled "Artificial Intelligence vs. Engineering Intelligence" with some pertinent conclusions for all maritime engineers, to be read directly across to ship designers. Firstly, the ESTIN authored article usefully gives detail on some nine ML algorithms, some of which are already used in the maritime sector and their Figure 8 breaks these down into three categories regarding their use. This scheme is then applied to analysing predictions for the propulsion system of a 9500 TEU container ship, addressing: Brake Power; Propeller Diameter; and material classification. Unfortunately, this seems a little prosaic alongside Bernstein's holistic review concerning architectural practice or possible ML applications with similar broad scope to whole ship design practice. Perez Fernandez RINA lecture was more of a grand overview and concluded, while software engineers may well be an "AI threatened species", naval architects and marine engineers were far less threatened, as the nature of their tasks and responsibilities were much more diffuse and he considered "the threat of AI is overblown". The latter was justified by Perez Fernandes because he considers that AI requires the human on top and he felt AI was a sub-set of "Engineering Intelligence". More likely AI might give engineeringly creative professions (particularly in the complex and diverse maritime sector) more time to achieve "better ship designs"? However, given a more radical response to ML by Bernstein (2022) on behalf of the holistically design focused architectural profession, Perez Fernandez view could leave the ship design fraternity exposed, if we are too relaxed?

6. CONCLUSIONS

6.1 Why Ship Design is different to so much of Engineering Design

The first conclusion on the expanding scope of ship design is that even before this paper addressed the topic, the nature of ship design, when compared to most engineering design and other forms of large-scale design, such as architecture, is different, not just in the product (ships) but also the process. Both are particular and quite diverse across the maritime domain. There are other physically and large products/systems, as outlined before (Andrews, 1998), but both the ever-changing ocean environment and the mobile, long endurance, inhabitable entities we design, challenge many aspects of engineering analysis, construction and the design process. So, there is a need to train ship designers in naval architecture, not just on the traditional fundamentals (i.e., Brown and Andrews' (1980) "S^4") but also the 5th "S" of Style issues. Furthermore, that knowledge has expanded and, while covering the fundamentals, advanced topics (like the examples given by the third set of bullets at Section 4.4) have to be formally understood from first principles. This is so that the over-arching ship designer can both quiz the growing bands of different deep specialists and ensure their inputs are incorporated appropriately within the whole ship design context. Reference has already been made to the issue of Design Authority (see Section 3.4 - third paragraph), which for ships can only sensibly be executed by a naval architect, not a generic systems engineer or domain knowledge limited manager. Thus, it is ethically wrong for ship safety certification to be signed off by senior (unqualified) personnel, as it is the senior most naval architect in a ship project with whom realistically the buck stops on most of whole ship safety (Andrews, 2021b).

Beyond the "S^4" NA issues, there is the whole ship design (with Style issues summarising much of where the ship designer leads) covered by the six items listed in Section 3.3 and the three bullets of Section 3.5. If in addition the nine issues raised by the very first IMDC SoA report and listed at Section 1.2 are revisited, almost three decades later, it can be seen that many have been responded to over that time, not least in the subsequent conferences. Not all are resolved but most have been progressed and the remaining issues are appropriate (even with ML and current AI upon us) for future IMDCs to take forward. It was interesting that in the year's delay to the XIV IMDC at Vancouver, due to Covid-19, the International Committee rejected a virtual conference in 2021. It was not just felt that a full physical conference was nice to have but rather it was essential for the next generation of new researchers in ship design to present in person and openly discuss their ongoing research with the marine design community.

6.2 The Future of Ship Design Practice

Although I have both called for a clear, if creative and non-prescriptive, approach to the manner in which ship design should be undertaken and, in this paper, which has discussed the growing diversity of ship/marine design, this is now considered in the forward-looking conclusion of this wide ranging and summary review. Thus, it is considered worthwhile to also list some of the questions I have proposed over the last decade in addressing future ship design and its practice. This is done in Table 2, which poses these questions, all of which are directly the titles for a set of recent design methodological papers. I leave it to the next IMDC in June 2027 to take up any or all of these questions, where my initial response to each question posed is given in the initial publication referenced.

Table 2: Questions for the Future of Ship Design

	Andrews' suggestions as to Ship Design Methodology Issues still needing to be addressed.	Initial/Key Andrews Reference
1.	Is there "Art and Science in the Design of Physically Large & Complex Systems"?	Proc.Roy Soc London, Part A, April 2012.
2.	What are the "Philosophical Issues in the Practice of Engineering Design"?	Phil Eng, Vol.1 of Proc, RAEng, June 2010.
3.	"The Nature of Requirements Elucidation?"	IJME/TRINA, Vol.153, Part A, 2011.
4.	"Is Marine Design a Mature Discipline?"	Proc XI IMDC, June 2012.
5.	What is the "True nature of Ship Concept Design?"	Proc COMPIT, May 2013.

6.	Do "Ship Project Managers need to be Systems Architects, not Systems Engineers?"	RINA Conf. Maritime Project Management, Feb. 2016.
7.	"Does one size fit all or do different designs require different Ship Design Processes?"	RINA Warship Conf. June 2016.
8.	"The Key Design Decision: Choosing the Style of a specific ship design option"?	IJME/TRINA Part A4, Vol. 159, Oct 2017.
9.	"Do future Ship Designers need to be Human Factors Experts?"	Proc COMPIT, May 2018.
10.	"Is a NA an atypical Designer or just a Hull Engineer?"	Proc XII IMDC, June 2018.
11.	What is "The conflict between Ship Design and procurement policy?"	RINA Warship Conf. Sept 2018.
12.	Is "ESSD for Complex Vessels really Sophisticated?"	IJME/TRINA Spec Ed. Vol.160, Oct 2018.
13.	How important is the "Fuzzy Half of Ship Design?"	SNAME, SMC, Houston, 2022.
14.	"Is there an Expanding Scope of Submarine Design?"	Submitted 2024.

6.3 An ambitious vision of Where Ship Design may Lead

One future vision for a better and more holistic approach to ship design, based on the issues raised in this paper, would be to apply the future ship design practice called for to future "physically large and complex systems". The obvious maritime extension is to "inner space" or subsea habitats (Divemagazine, 2024). Perhaps not so obvious, unless my architecturally based approach to early stage design synthesis is seen as applicable beyond marine vessels to other PL&C systems, is future space "ships", where the latter word is of course "a giveaway". In fact, the architecturally DBB SURFCON module in QinetiQ's Paramarine SD suite (Qinetiq, 2019) has been used in UCL student projects to design both a low terrestrial orbiting "Space hotel" (Bowditch, 2011) and an interplanetary "Spaceship" (Downton, 2023). It is argued that these large vessels are like many complex marine vessels, sensibly designed from "inside out" in a similar manner, and where achieving the naval architectural balance of the DBB "Master Building Block" (Andrews, 2018a) is replaced by the demands of the physics of terrestrial orbiting or interplanetary travel, respectively. The point being this is an extension of ship design methods and practice, which is more applicable than the aeronautical design approach (e.g., Mavris et al., 1998) used for current space "craft' (i.e., small vehicles for few people for short journeys). The ship type issues of no full-scale prototypes and bespoke design on a large scale, reinforce this analogy.

To round off this look at future ship design practice, I go back to my first formal publication on ship design, which led to my 1984 PhD thesis (Andrews, 1984), and was boldly entitled "Creative Ship Design" (Andrews, 1981). I would argue that the point behind that paper is more than ever relevant, given the "threat" of AI/ML. Thus, the routine approach to much of the practice of ship design would seem to be likely to be subsumed by tools driven by ML (and then AI) and the issues identified by Bernstein (2022) for urban architecture and planning will totally alter the human-machine design relationship. What will (hopefully) be left with the human ship designer will be the "creative" aspects of designing complex entities, hence the referral back to the 1981 "Creative Ship Design" paper, which originally argued for an architectural design synthesis (the inside-out approach) and thus to expand the ship synthesis from sizing, just to achieve "naval architectural balance" (i.e., S^4), into the harder challenge of the wider (e.g., HF driven) design needs. This challenge has been (at best) left by ship designers until too late in most current designs, namely well after the concept phase and thus when only highly constrained options are then practicable. Underlying this early creative call was a desire to make the design of ships better recognised (by the profession, our stakeholders and wider society) as one of the most sophisticated endeavours done by designers of complex systems and for that to be done to its best, requires a creative and open mind set.

6.4 Author's contribution to Expanding Ship Design Practice

I am conscious that a new reader to this paper's exposition of many previous voicings, of its messages on ship design, may consider there is too much presented of this author's many ship design publications. However, I consider these are best encapsulated in the 2018 major statement (Andrews, 2018a) that permeates much of the current paper. As the originator of not just the architectural approach to ship synthesis (Andrews, 1981, 1984) but a strong believer in the fascination (Andrews, 2006a) and creativity (Andrews (1981, 2003a, 2012)) in the design of "ships" (of all types – so maybe vessels or marine design is a better term?), I attach at Appendix B a summary (Table B1) of my specific main contributions to the field of ship design methodology. This tabulation is presented as it summarises the innovations originated in a career in ship design, covering practice (Table A1), teaching and research (Table B1). As such this paper may well be my last IMDC contribution. It should, therefore, be seen as making the argument for the expanding scope likely for future ship design practice, and as such leaves a clear challenge to my current colleagues and future successors.

Given I have always considered that a good designer ought to look to those beyond their own ilk, I have attached two prescient quotes above my Introduction, which ought to be taken to heart, regardless of the future posed by ML and AI for our profession.

ACKNOWLEDGEMENT

As already mentioned, this is likely to be the author's last major contribution to an IMDC, having been a contributor since the VI IMDC, member of the International Committee from then, initiator and lead editor for the SoA reports from 1997 to 2018 and International Chair from 2015 to 2022. So, I want to thank my past and present colleagues on the International Committee, past chairs of the Local Organising Committee of each of those nine wonderful conferences and, not least, the very many contributing authors, who efforts made each conference a success, and finally all the other attendees, who gave life to each conference and sustained we believers in the magic that is ship and marine design, in which I feel privileged to have spent my professional life, and met so many committed colleagues.

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APPENDIX A

Table A1: A Summary of the Author's Involvement in Major UK Warship Designs as a Naval Constructor (1972-2000) (see Section 2.1 of Andrews (2018a) for further detail on most listed designs)

UK Warship Project	Time span of Author's Involvement	Role played by Author	What Drove that design	Key lesson from design/project
SWIFTSURE SSN	1973-75	Assistant Constructor –Structural design + Cold Bent Frame Investigation	Combating Soviet SSNs – Acoustic Performance	Even the best designs can have critically unforeseen problems (e.g., Cold bent frames (Faulkner, (1983)) Building in generous margins can reap major benefits beyond that design
SSNOY (Became TRAFALGAR Class SSN)	1974-75	Assistant Constructor-Structural new design + lead calculator	Step change from SWIFTSURE Class – New sonar + new reactor	Ended up too ambitious, so replaced by very successful Batch 2 Swiftsure Class (Trafalgar Class); Could be seen as akin to USN SEAWOLF experience – but UK Changed to Batch 2 Swiftsure.
INVINCIBLE Class CVS	1975-78	Constructor (Air and Weapons integration)	Initially ASW helo carrier with provision for a few STOVL	Modern light but medium sized carrier; First all Gas Turbine propelled major warship saved 30% crew; FBNW STOVL modified while building to take new FRS Sea Harrier (author led on fit to CVS)
Type 23 Frigate	1978-80	Lead Concept Designer (TA Tug with CODLAG)	To provide GRIUK Barrier + Merlin Helicopter	Do not design to precise OA scenario (ISD 1989 – End of Cold War) Ships then became GP with gun and PDMS. Lacked margins for adaptation or enough accommodation
FORT Class AOR	1978-80	Lead Concept Designer (one stop logistics support to Type 23 in GRIUK gap	Commodities + 4 Merlin Helicopters full Support	Became main fleet support when Cold War role collapsed. Trying to mix a warship capable AOR with RFA standards meant cost excessive.
SANDOWN Class SRMH	1978-80	Lead ship concept design	Cheaper version of Hunt MCMVs	Example where shipbuilders' competition led to real build innovation by Vosper Thornycroft Shipbuilders
Various Frigate/CV Studies	1978-80	Lead Concept Designer (series of Hilo mix studies)	Square the circle of affordability +Exportability	Need to explore options widely to provide better basis for naval decision making on future ships and ship Research & Development.
VANGUARD Class SSBN	1984-86	Head of Hydrodynamics + Structural Design	Provide national Nuclear deterrent Submarines.	Assembled "A Team" to do the design in-house with top priority to deliver fully to time, within cost, meeting national capability
LPD (Replacement) Class	1986-90	Warship Project Manager for Replacement Amphibious Fleet	Concept studies on up lift capability ro-ro LCUs	Key Amphibious Units. Author forced to adopt Proc Strategy (build to specification by 3 industry teams) that then failed as MoD needed to lead design. Reverted to MoD led design.

UK Warship Project	Time span of Author’s Involvement	Role played by Author	What Drove that design	Key lesson from design/project
ASS/LPH OCEAN	1986-90	Warship Project Manager for Replacement Amphibious Fleet	Cheap helicopter carrier Thought possible without costed studies by senior naval staff	Flawed concept by non-ship designers without concept/feasib design. Proc strategy: fixed price even non-naval standards unaffordable. Got un-survivable High Value Unit (12 Helos + 800 Marines +vehicles) not sensible (Andrews 2018b).
RFA ARGUS ATS	1986-90	WPM to “get out of shipyard” (major conversion)	Ro-ro Container ship converted to helicopter training	Example of how not to procure a warship (see Andrews (2018b)) even on an apparent Fixed Price contract. Used by senior staff to explore Hands-off, so Major cost hike.
HMRY Replacement	1988-89	WPM conduct one-year Special Design Study for Head of State	Replacement of HMRY for No.10 and Head of State	Find cost of Replacement to modern standards – electric power/reduced crew/enhanced Public Spaces/helicopter landing/modern comms & security
Wave Class AO	1990-91	Head of Concept Design	Replace existing Fleet Oilers	Staff (OPNAV equivalent) “awaiting Fleet Studies ” so author produced concept design; first navy double hulled tanker. Do not need OA when in a hurry to replace fleet assets.
Future Surface Combatant - became Type 26	1990-93 and 1998-2000	Head of Concept Design then Project Director	Main ASW Escort + general combatant	Not driven by major weapon but Adaptability – which MoD system found hard to model/approve; MoD approval system built on weapon capability not TL adaptable naval presence.
FCV (became QE Class Carriers)	1991-93	Head of Concept Design	Strike carrier STOVL/ CTOL	Needed to get large carrier adaptable to STOVL or CTOL. Basis of internecine RN-RAF “ warfare”. Navy finally got capability by Carrier Alliance of MoD with main shipbuilders.
CNGF (became the T45 Destroyer Class)	1991-92	Head of Concept Design as Member of Anglo-French Steering Group	Fleet AAD-PAAMS escort	Example of single weapon system (PAAMS) dominating design. But major Machinery and Accommodation needs also drove size. Collaboration (UK/FR/IT) not easy, so reverted to Type 45.
FASM (became FSSN)	1990-92	Head of Concept Design	New SSN: post-Cold War	Need to change design approach (SUBCON based on author’s Building Block approach) to explore solution space widely.
RV TRITON First Trimaran Ship	1990-93 and 1998-2000	Head of Concept Design then Project Director for acquisition	2/3rd scale Prototype Trimaran Destroyer	Needed prototype (on cheap) to explore novel hull form (with steel structural design) and “win hearts and minds” of operators – successful but through USN LCS programme.

List of Acronyms in Table A1 (in order of first usage in Table A1)

SSN – Nuclear powered submarine
SSNOY – OY was second class of “new” SSNs to follow the 1970s Swiftsure Class (SSNOX)
USN – United States Navy
CVS – (Aircraft) Carrier (Support) – not Fleet (Attack) carrier
ASW – Anti-Submarine Warfare
STOVL – Short Take-Off and Vertical Landing Carrier Aircraft
FBNW – For But Not With – Ship designed to receive (weapon) fit but not installed on build
FRS – Fighter, Reconnaissance and Strike – designation of the UK Sea Harrier STOVL Aircraft
TA – Towed Array – Passive Sonar Array for ASW
CODLAG – Combined Diesel Electric And Gas(Turbine) ship propulsion fit
GRIUK – Greenland, Iceland and UK Gap – Cold War ASW choke point
OA – Operational Analysis
1SD – In-Service Date – for naval vessels Acceptance into the Fleet

GP – General Purpose – Designation for combatants with all-round capabilities
PDMS - Point Defence Missile System – last ditch AAD against missile attack
AOR – Auxiliary Oiler Replacement – One stop fleet replenishment vessel
SRMH – Single Role Minehunter – MCMV with single (detection) role
MCMVs – Mine Counter Measurers Vessels – broad MCM designation
CV – (Aircraft) Carrier
SSBN – Ballistic Missile delivery nuclear powered submarine – Nuclear Deterrent armed
LPD - Landing "Platform" (Dock) – Amphibious Warfare (LCU delivery) vessel and Force Command
Ro-ro LCUs – Roll on/Roll off Landing Craft (Utility) – new LCU concept for 1980s RN LPD
ASS/LPH – Aviation Support Ship became Landing "Platform" (Helicopters) – Amphibious Vessel
RFA – UK Royal Fleet Auxiliary – RN ships operated by Merchant ship "company" rules
ATS – Aviation Training Ship – RFA to train helicopter operations at sea
AO – Auxiliary Oiler – Fleet support tankers for underway replenishment
FCV – Future (Aircraft) Carrier
QE Class – Queen Elisabeth Class UK Attack Carrier Class
TL – Through Life
CTOL – Conventional Take-Off and Landing (Aircraft operated from Carriers with catapults and arrestors
CNGF – Common New Generation Frigate – designation of Anglo-French 1990s AAD combatant project
RN-RAF – UK Royal Navy and Royal Air Force
T45 – Type 45 – designation of RN AAD Destroyer class replacing earlier Type 42
ADD-PAAMS – Anti-Aircraft/Air Defence- Principal AA Missile System – fitted to Type 45
UK/FR/IT – UK France and Italy combined project for AAD (PAAMS) combatants – became T45 (UK) and Horizon (FR/IT)
FASM - Future Attack Submarine – UK replacement for current ASTUTE Class SSNs
FSSN – Future SSN – later designation for FASM (1990s/2000s)
SUBCON – SUBmarine CONcept - concept design tool developed by UK MoD/BMT Icons in 1990s using UCL DBB approach (BMT Icons– British Maritime Technology – Icons formerly BSRA now Aveva)

APPENDIX B

Table B1: Andrews Specific major contributions to Ship Design Methodology

	Andrews' contributions to Ship Design Methodology	Initial Reference	Subsequent verification in Ship Design
1.	Inside-out approach to ship design synthesis.	Andrews (1981)	Andrews (1984)/(1986)/(1987)
2.	DBB realisation of inside-out ship synthesis	Andrews & Dicks (1997)	Andrews (2018a), Andrews&Pawling (2003, 2008)
3.	The importance of constraints on SDP	Andrews (1981)	Andrews (2018a)
4.	The importance of Style in going from function to form	Andrews (2012b)	Andrews (2017, 2018a)
5.	Requirement Elucidation NOT Requirements Engineering is aim of the Concept Phase	Andrews (2003a)	Andrews (2011, 2022)
6.	Proposing a 3-D ship solution space	Andrews (1993)	Andrews (2012b, 2018a)
7.	Identifying that the level of Novelty requires different design approaches/methods/tools	Andrews (2012b)	Andrews (2016a, 2016b, 2018)
8.	Showing the fuzzy "half" of ship design is a human driven decision process	Andrews (2012b)	Andrews (2012, 2018a, 2018b, 2018c, 2018d, 2022, 2023), Andrews & Andrews (2021)