MARINE REQUIREMENTS ELUCIDATION AND THE NATURE OF PRELIMINARY SHIP DESIGN

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SUMMARY

In 2003 the author produced a paper, entitled "Marine Design – Requirements Elucidation rather than Requirements Engineering", for the 8th International Marine Design Conference. This was intended to follow on from van Griethuysen's 2000 IMDC paper "Marine Design – Can Systems Engineering Cope?", while drawing on the author's recent experience in, firstly, directing and then being the MoD Future Surface Combatant (FSC) IPT Team Leader in the concept phase for that programme, where the intentions of Smart Procurement were applied. Since leaving the MoD in 2000, the author's academic endeavours, at UCL, have both refined the ideas in the 2003 paper and, through a diverse range of ship design studies, provided further substantial evidence in favour of that paper's argument. The current paper was originally presented to the first Institution conference on systems engineering. This is a revised version in the light of the discussion at that conference on the applicability of systems engineering practice to initial ship design and presents the arguments of both papers to a wider audience.

The current paper looks at the origins of the concept of Requirements Engineering, within systems engineering, when specifically applied to naval engineering acquisition practice. This is contrasted with consideration of the actual nature of the initial design of physically large and complex systems, typified by modern naval vessels. This is followed by drawing specific insights from a series of design studies undertaken by the UCL Design Research Centre, under the direction of the author. These diverse and wide ranging initial design studies can be seen as examples of the sophistication of Requirements Elucidation, exemplifying how systems engineering practice can be applied to the critical early stages of naval ship design. The paper concludes by looking at the characteristics of the initial or concept design process by seeing Requirements Elucidation, as the strategy to tackle the inherently "wicked problem" of determining what is really wanted of a naval vessel and what can be afforded.

1. INTRODUCTION

In 2003 the author produced a paper, entitled "Marine Design – Requirements Elucidation rather than Requirements Engineering", for the 8th International Marine Design Conference [1]. This was intended to follow on from van Griethuysen's 2000 IMDC paper "Marine Design – Can Systems Engineering Cope?" [2], while drawing on the author's recent experience in directing and then being the MoD Future Surface Combatant (FSC) IPT Team Leader in the concept phase for that programme, where the intentions of Smart Procurement were applied [3]. As indicated by the 2003 paper's title, it concluded that the practice of first investigating, in considerable depth and importantly in non-material specific terms, the requirements for a major naval programme was

a) not appropriate for major warships – such as the FSC;
b) bad Systems Engineering practice – corroborated, at that time, by the views of a senior systems engineering theorist [4].

With such clear conclusions, it might be questioned as to why the issue merits revisiting? This is seen to be necessary because the practice of such "Requirements Engineering" still seems to be prevalent and underlies, despite all the evidence to the contrary, two further misapprehensions, namely that:

a) Systems engineering can be seen as a design discipline separate from domain specific disciplines, such as naval architecture, in the field of ship design. This then leads on to the view that S.E. can be regarded as more than a methodology, whose primary function is to ensure best practice project management principles are adopted by project teams [5];
b) Physically Large and Complex (PL&C) systems, like warships, can be designed in a manner akin to software led systems, such as air traffic control systems or warship combat systems. This then assumes the physical architecture of the combat system can be left not just until the abstract requirement statement has been finalised but also subsequent to producing the functional data flow system design [6].

Thus the current paper revisits both the issue of Requirements Engineering and what is argued to be the preferable process of Requirements Elucidation, in the hope that the appropriate practice is adopted in future warship design.

The paper commences with a consideration of the origin of Requirements Engineering and why it was conceived as being the appropriate process to adopt when considering the need for a new complex system and to do so in non-material specific terms. Next the nature of pre-feasibility or initial/concept design studies, as practiced for the acquisition of major naval vessels, is outlined in order to appreciate just how diverse this is and how, in particular, this diversity is addressed by the author's research team at UCL. It is then sensible to reinforce that general outline by describing a wide range of recent ship concept design studies. This is a change from the 2003 paper, which considered the initial design of such PL&C systems through the specific example of the FSC. This change is done to show the variety of studies typical of early stage ship design and that they all exhibit, to a greater or lesser extent, the characteristics identified in the approach designated by Requirements Elucidation. This approach is seen to be the fundamental objective of early stage design of such PL&C systems, for which the characteristics of this phase of design have previously been denoted as "wicked" by architectural and planning theorists [7]. From consideration of these diverse examples it is possible to consider what is required to be done in initial design to enable a major project to proceed into actual design evolution. The author has identified five characteristics, which are seen as clear indicators of the information necessary at the end of the concept phase in order to proceed into the remainder of the ship design process. In addition the issue of identifying the style of the emergent solution is seen to be critical and requiring a more descriptive concept definition than has historically been deemed sufficient. Thus it is possible to conclude what the desired Requirements Elucidation process requires, by way of an initial design synthesis, and why this approach is totally compatible with good project management (and systems engineering) practice.

2. THE ORIGIN OF REQUIREMENTS ENGINEERING

The origin of the notion of Requirements Engineering within a systems engineering approach would seem to lie with a change in emphasis in the defence acquisition field post war initiated by the US military. That was to a focus on military capabilities rather than equipment performance [8]. This was strongly enshrined in UK defence procurement with the Smart Procurement Initiative in the late 1990s and was illustrated in the 2003 paper with two figures [1]. These showed the make up of the key "non material solution specific" Requirement Engineering products, the User Requirements Document (URD) followed by the System Requirement Document (SRD). Their relationship to "System Design" was spelt out by van Griethuysen (2000) in the systems engineering iconic "waterfall diagram", which (drawn from INCOSE's 1991 statement) showed a sequence of the URD then the SRD and finally System Design, without any feedback. This approach was further highlighted in the 2003 paper by drawing attention to the URD and SRD being in accordance with Smart Procurement principles through being "functionally expressed and "engineered" ... (and) assiduously avoiding material solutions" [1].

So where did this strong prohibition, against any reference to material solutions, in deriving the capabilities needed by the user and, even more bizarrely, in producing the SRD, as the statement of the "system engineers 'own' requirements" [9], actually come from? The text quoted as the authority in the Smart Procurement process was the book entitled "Systems engineering – coping with complexity" written by four co-authors from the (then) Defence Evaluation and Research Agency (DERA) systems and software engineering team. Chapter 3 of that book, went so far as to be headed "Defining the solution in abstract" and then stated this was "showing what the system will do but not how it will be done." The book's authors then clarified that the writers of a SRD as designers, planners and systems engineers (note not the end users or requirements owners) "write requirements that do not necessarily constrain the solution …(the SRD being seen) primarily as an artefact needed for development" [9].

It would therefore seem that the origin of such an approach to "Requirements Engineering" lies clearly in software engineering where both the appropriateness of specifying user and system requirements in abstract has some logic and the focus on "development" prior to design is consistent with software production. However it is wholly inappropriate to then read this across to material products, such as complex constructions constituting warships and their land based equivalents of large-scale physical infrastructure projects. Interestingly, Brook (one of the co-authors of the DERA book and subsequently Director of Systems Engineering in DERA) in an influential paper in 2000 [10], summarised the "basic systems engineering processes" with a diagram reproduced below as Figure 1, which clearly shows the three steps (for URD, SRD and "System Design") as a "trade off triad" "that may have to be traversed in a number of iterations" and very importantly the arrows linking the three are not sequential but in both directions between all three elements. Furthermore Brook then denotes System Design as "Architecture – High level design" which is said to define the principal components and an overall architecture: terms with which a naval ship designer would feel entirely comfortable, as descriptive of ship architecture [11].

This more interactive set of processes is also reflected in the much more realistic 'waterfall' model, also reproduced here, as Figure 2. This version was the centre piece of the Royal Academy of Engineering's 2007 guide written by the Academy's Working Party on Integrated Systems Design, consisting of the UK foremost systems engineers. The Guide entitled "Creating systems that work: Principles of engineering systems for the 21st century" [12] gives six principles for integrated system design, the third of which "Follow a disciplined procedure" is illustrated with Figure 2. In this procedure the start of the whole process is absolutely not a requirement neatly enshrined in a massive URD but another interactive triad, shown in the first "bubble" and is much more inclusive and less prescriptive. The three interacting elements in that first bubble are "what do the stakeholders want?"; "what are the possible solutions?";

and "cost, timescale and risk". Thus not only the requirements owner has needs to be encapsulated but so do all the other stakeholders; there is a set of solutions to be explored (and only the designer can lead on that); and the process of finding out what is wanted is absolutely informed by cost, time and risk. The latter three can only be addressed, for physically realised products, through physically realisable design solutions, which then give the consequences of different design solutions. It would seem redundant to make the latter point if it wasn't that considerable effort continues to be expended on defining requirements and solutions "in abstract". In fact the MoD Smart Procurement process even set up the DPA's Future Business Group, which boasted that its role was to produce "solution independent requirements". And it was just such a statement that provoked the repost by Cranfield University's Professor of Systems Engineering highlighted at the conclusion of the 2003 IMDC paper [4]. Rather it can be seen from Figure 2 that this first crucial bubble, through 'possible solutions', can then inform the capability statement and thus constitutes Requirement Elucidation, defined by the author as being the primary task of the Concept Phase of design.

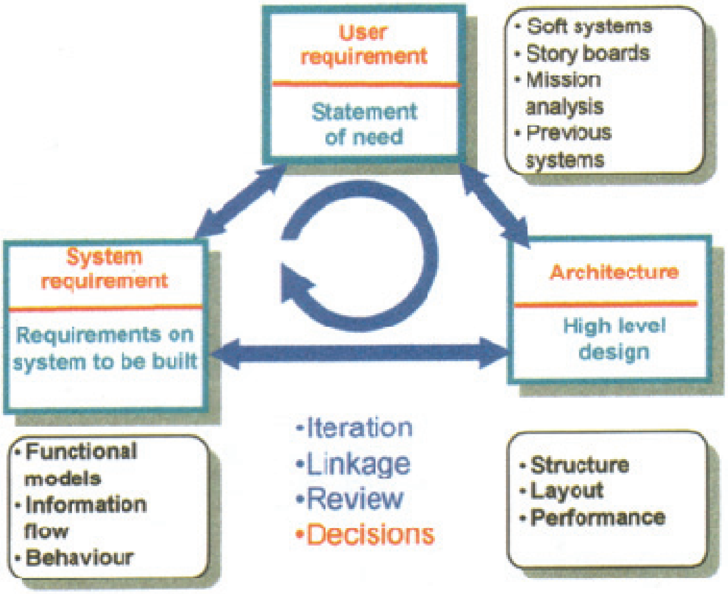

Figure 1: Basic systems engineering processes [10]

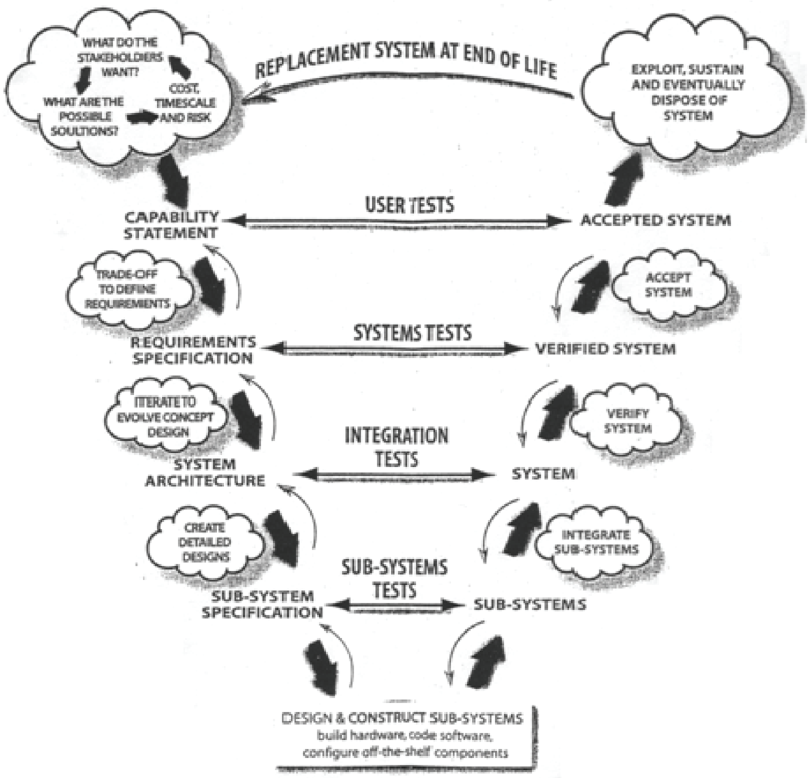

Figure 2: V Diagram due to the 2007 RAEng Guide to Systems Design [12]

There might seem to be some justification nevertheless in a purely abstract approach to formulating requirements, as espoused in the DERA book [9], when it comes to combat systems design, given such systems are largely dominated by software issues. For combat management systems certainly, abstract statements of data flow logic can be obtained directly from functional statements of requirement. However John's comments at a general systems engineering level [4] clearly emphasise the need for a range of solutions to be explored in any complex system design process. Furthermore, most weapon and sensor systems within a warship's overall combat system fail, or at least have performance drop-offs, due to physical (engineering) aspects receiving too little attention *vis a vis* the abstract system architecture [13]. It has been the case for some time that, when incorporating combat system equipment into naval combatants, there has been too little regard given to the issues of physical integration and the effects of the extreme physical environment. The author, as a naval architect, had responsibility for integrating weapon systems into a major ship design [14] and feels the ship design discipline has abrogated this responsibility to a discipline less focussed on the physicality of the ship and less aware of whole system (warship) cost and ship performance implications.

Less this false god of "Requirements Engineering" be seen as a purely British aberration, it is worth considering the approach in the USA, where the post-WWII emphasis on capability could be said to have originated the "abstract" approach [8]. The US Navy has long advocated a "Total Ship Systems Engineering" approach, which sometimes seems to subsume the naval architect's or ship designer's role of co-ordinating or "leading" the whole ship design [15]. Thus Calvano et al [15], although extremely experienced naval ship designers, feel obliged to define the "functional analysis and functional allocation process" in getting "from customer performance goals to design requirements in a rigorous, complete and traceable way". This is done through a block-diagram approach so that the "function blocks should represent *what* must be done, not *how* to do it". Thus one can see an emphasis on abstraction, which is counter-intuitive to designers of engineering physical systems (such as ships). It is also considered that this abstraction also presents operational users, trying to spell out what they want, with immense cognitive difficulties in identifying appropriate capabilities to do future tasks. This identification can only be done by drawing on their experiences of operating current real ships and systems, yet they are expected to spell out such capabilities without ostensibly picturing potential physical solutions. I would argue that this abstracting of capabilities is not just false, in that physical solutions are necessary to arrive at non-material (functional) requirements. It is also highly inefficient, in that deriving capabilities without cost and feasibility checks can lead to "dead-ends". Commitment to such protracted Requirement Engineering has further extended the front-end decision making for such politically sensitive programmes and, in recent years, too often resulted in programme delay.

If we agree that like the designing of large complex buildings or sets of buildings, such as airports and town centres, the design of naval ships is characterised by the "wicked" nature of the design process [7], where

"formulation of a 'wicked' problem is the problem. …setting up and constraining the solution space… is more essential than the remaining steps of searching for a solution."

Then this explains in part why the formulation of requirements is inherently difficult, but also why this is intimately interwoven with the search for and exploration of solutions. Sorting out what a multi-functional, independently operated vehicle, containing a hundred or more highly trained personnel, might need to do in a very uncertain future can only be explored in terms of possible design options. Furthermore cost, time and risk have to be taken into account (see top "bubble" of Figure 2), in moderating any needs expression by the achievable and affordable. Thus the case for solution exploration is not just to inform the requirements owner but also to ensure the designer is an equal partner in the dialogue. This means dialogue is then precisely what is meant by Requirements Elucidation.

3. THE BASIS OF SHIP CONCEPT DESIGN STUDIES

If the object of the first phase of naval ship design is that of Requirements Elucidation in tacking the "wicked problem" of finding the achievable and affordable requirement, for such a physically large and complex system, then it can be seen to be quite different to the subsequent phases of design. Those subsequent sequential phases, typically denoted as Feasibility, Ship Design, Contract Design/Definition and Detailed Design, are essentially about working up the design so that it is shown to be technically achievable and then producible in the built product. To understand better the unique role of the Requirements Elucidation process it is considered worth reprising the description of the concept phase for a putative naval vessel, before showing a range of concept level studies undertaken by the UCL DRC in recent years. These studies were in part exploring the characteristics of this crucial front end of the design process for such physically large and complex systems.

At this point it is worth stating a truism, that each ship project is different in its objectives and constraints from all others. Thus the approach advocated in this paper is seen as primarily justified for major naval ship programmes, despite there still being distinct advantages in its adoption for lesser projects. However in the latter cases, the timescales and scrutiny process are considerably shorter, often to meet a more limited and, hence, clearer imperative. This range of acquisition complexity is mirrored in the range of ship design sophistication highlighted by the author at Table 4 in the IMDC 2006 State of Art Report [16] and reproduced below as Table 1. It shows a spectrum of approaches to ship design, distinguishing them by the relative novelty in the types of design and hence the design resources demanded for them to be undertaken. Beyond this it is also worth stating that the nature of preliminary ship design has been spelt out by various practitioners and many of these expositions have recently been reviewed by the author, as part of a paper with a co-worker, in a detailed presentation of preliminary ship design [17].

Finally in emphasising the importance of preliminary ship design, it is considered useful to reiterate that it is the only time designers can be truly divergent and radical in their thinking. If new and different options are not considered then, they never will be; if the designer doesn't push the requirements owner to stretch the requirement, again the chance will not come downstream once the design team is on the roller coaster of project management. The design team should enter that downstream process with confidence in their choice of option to be developed. This is best achieved by a comprehensive and wide design exploration in the concept phase. Without this the team remains vulnerable to the many likely attempts to deflect and challenge their chosen design and its development. All this argues for increased investment by the wider design community in the front end of the ship design process, which is essentially the Requirements Elucidation task.

Table 1: Types of Ship Design with Examples from Naval Ship Design [16]

Type	Example
second batch	Batch 2 Type 22 frigate
simple type ship	many naval auxiliary vessels
evolutionary design	a family of designs
simple synthesis	UCL student designs
architectural synthesis	UCL design studies
radical configuration	SWATH, Trimaran
radical technology	US Navy Surface Effect Ship

Before considering the manner in which the initial phase of ship design ought to be carried out, it is considered sensible to spell out, in a little more detail, the overall concept process for a major new naval ship design. This can be done in terms of three initial overlapping design stages, comprehensively presented in the author's 1994 paper on the preliminary design of warships [18]. Outlining each stage in a little more detail:-

3.1 CONCEPT EXPLORATION

This initial design stage can be said to comprise a wide-ranging exploration, which starts at the initiation of investigations for a new ship design. It should be an extensive consideration of all possible options and, typically, include modernising existing ships, modifying existing designs and exploring the full range of, for example:

(i) packaging of the primary function (e.g. aircraft, weapons or sensors for a combatant; cargo/passengers for naval auxiliaries or, even, merchant ships);
(ii) capability of the ship to deliver the functions (e.g. speed, endurance, standards);
(iii) technology options to achieve the functions and capability (e.g. existing technologies, enhanced materials and systems, enhanced technological/ configurational options, reduced technology levels).

These explorations may well be cursory or may show the need to further pursue more than one distinct option and may require research programmes, to de-risk key technologies, or revisiting (not for the last time) the initial operational concept.

3.2 CONCEPT STUDIES

Assuming only one or two options are to be taken forward, the wide ranging but cursory nature of the initial exploratory stage is unlikely to have investigated in any depth the perceived design drivers and the impact of various choices on function, capability and technology. This next stage is dependent on the type of vessel (i.e. combatant, aircraft carrier) and degree of novelty (e.g. conventional monohull, unconventional configuration), as well as a range of issues to be addressed from payload demands through speed and endurance to style issues, such as those associated with design life, signatures, survivability and complement standards. All these issues normally merit investigation before the design is too fixed. They can also significantly influence the downstream design but, more importantly, they need to be debated with the requirements owner, since their impact on the ship's performance and affordability should be part of the requirements elucidation dialogue, before the form and style of the solution are too precisely fixed.

3.3 CONCEPT DESIGN

This final stage prior to approval to commit to a more substantial design effort (i.e. in UK MoD terms, prior to Initial Gate decision) is primarily focused on the design (and costing) information necessary to ensure the approval to proceed is based on sufficient information and that the process, beyond that approval, proceeds coherently. Typically, the stage is dominated by cost capability trade-off studies and the interaction with any associated operational analysis. It can be appreciated that to enter into this last concept stage with inadequate exploration of the solution space or of the style and performance issues, is unwise as any submission to proceed is likely to be vulnerable to probing, by approval authorities, on the impact of such issues. This just emphasises the inherently "political" nature of naval ship acquisition at the front end of the process and why it is often protracted and seen to be unsuccessful and apparently costly, in comparison with the process for even the most sophisticated merchant vessel. However it is still nothing like as expensive as the development processes for major aircraft programmes, given these include the production of several full scale prototypes. Rather than such extensive preproduction development, there are issues in the case of major naval programmes that are seen to need exploring which are more related to the environment in which design and acquisition are undertaken. This is a complex world well addressed in US Navy organisational papers (such as Tibbitts and Keane [19]) and, for the UK, in Reference 17 and its lengthy published discussion.

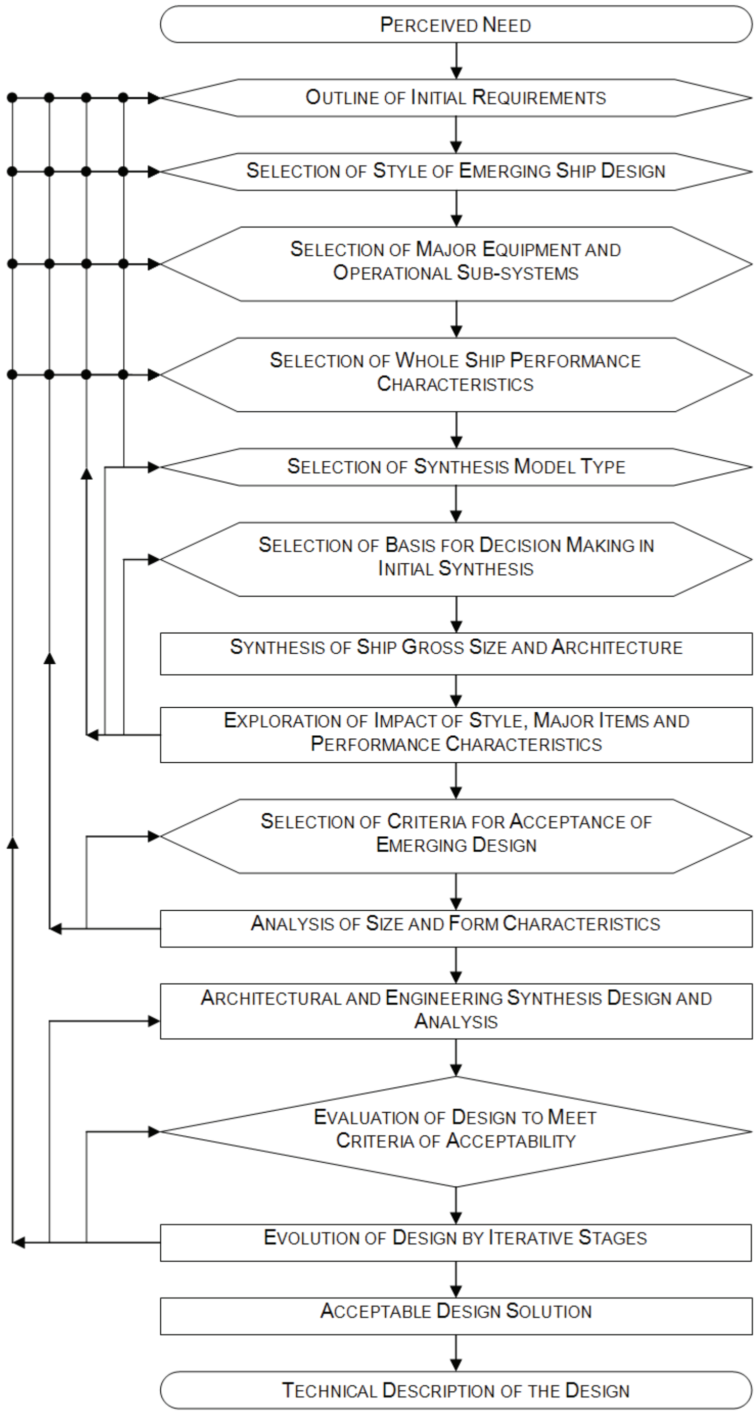

Figure 3: A Representation of the Ship Design Process Emphasising the Main Decision Choices

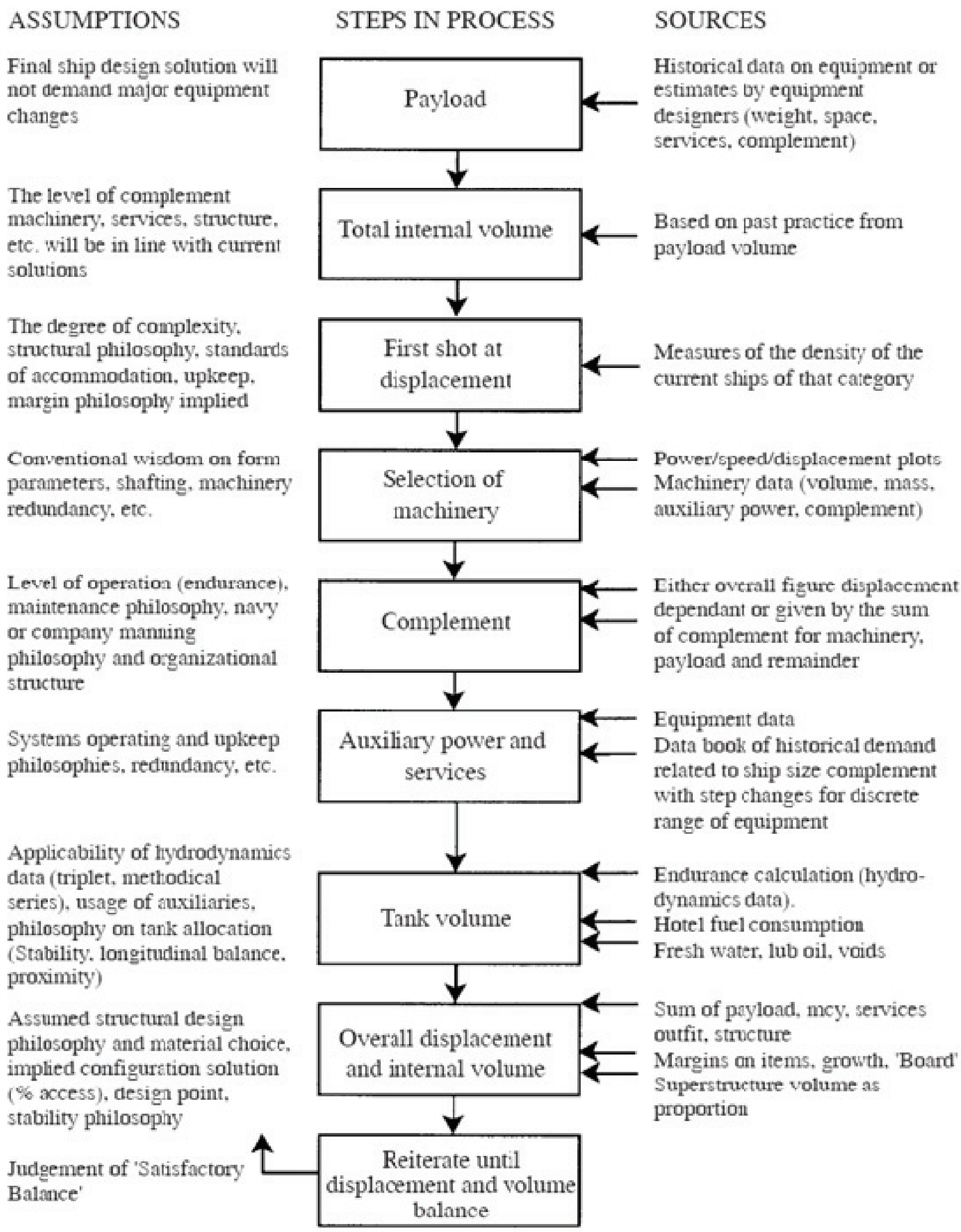

Figure 4: The Initial Ship Sizing Iterative Sequence showing Assumptions and Sources [20]

Having spelt out the main stages in a major new ship concept design process, it is worth focusing on the specific technical step in the representation of the overall ship design process (see Figure 3). The first part of the "Synthesis of Ship Gross Sizing and Architecture" step, namely the sizing process, was expanded in Reference 20 as "The Warship Initial Sizing Process" and is often referred to as a numerical synthesis. It is important to appreciate such iterative sequences have significant caveats underlying their adoption. This was reinforced in the author's comments at Reference 21 that such iterative sequences should not be used without acknowledging the range of caveats implied in their use. The complete Figure 4 shows, in some detail, the "Assumptions" and "Sources" typically behind any such numerically based synthesis. Finally it is worth remarking that the overall process diagram of Figure 3 has considerable feedback loops, not just to show reconsideration of the decisions on the various selections, starting with design style, but also feeding right back to the initial requirements. This can then inform the dialogue with the requirements owner and, as such, is consistent with the message of the first bubble in Figure 2.

Figure 4, representing the "traditional" numerical synthesis, can be compared with the much more comprehensive and sophisticated architecturally based approach to initial ship synthesis subsequently pioneered at UCL by the author and encapsulated in recent years by the Design Building Block (DBB) approach [20, 22]. The most extensive presentation of this approach was in Reference 17, which outlined in some detail each of the four main stages of the combined architectural and numerical synthesis process, where each stage produces an increasing level of definition of a new preliminary ship design. At each stage an appropriately holistic and numerically balanced definition of the ship design is produced, using assessments of as wide a range of performance aspects as is sensible at that stage in the design evolution. Table 2 summarises this process, giving typical design decisions taken at each stage and, for the example in Reference 17, the granularity of the design study for each stage (i.e. the number of DBBs). The detail provided for each evolutionary step is spelt out for the example trimaran Littoral Combat Ship investigation in that reference.

Table 2: Design Building Block design stages showing major design decisions and DBB granularity for the example in Reference 17

Design Preparation
Selection of Design Style
Topside and Major Feature Design Phase (18 to 47)
Design Space Creation
Weapons and Sensor Placement
Engine and Machinery Compartment Placement
Aircraft Systems Sizing and Placement
Superstructure Sizing and Placement
Super Building Block Based Design Phase (47 to 110)
Composition of Functional Super Building Blocks
Selection of Design Algorithms
Assessment of Margin Requirements
Placement of Super Building Blocks
Design Balance & Audit
Initial Performance Analysis for Master B.B.
Building Block Based Design Phase (110 to 343)
Decomposition of Super Building Blocks by function
Selection of Design Algorithms
Assessment of Margins and Access Policy
Placement of Building Blocks
Design Balance & Audit
Further Performance Analysis for Master B.B.
General Arrangement Phase
Drawing Preparation

The examples of concept design that are outlined in the following section were all produced by the UCL DRC using the DBB approach, rather than the limited numerical synthesis approach of Figure 4. While the latter has the advantage of speed of execution in achieving an iterative balance, it can only do so by assuming specific (but not necessarily appropriate) hull form parameters, as the right hand side of the figure shows. It then needs to be followed by a parametric survey, which itself is of questionable veracity (see argument presented in Reference 23). Whereas the DBB approach is a more fully integrated synthesis of weight, space, form and the architectural dimension, which further opens up the concept solution space, as can be seen from the examples in the next section.

4. EXAMPLES OF CONCEPT STUDIES

The ship concept studies presented in this section demonstrate the range of investigations that might be attempted under the broad category of initial, preliminary or concept studies, not with regard to types of ship roles (such as amphibiosity, logistics, air defence, land attack, escort or general purpose), ship types (such as combatants, aircraft carriers, LPD/H/A, submarines) or ship configurations (such as monohulls, multihulls, fast hull forms), but rather different concept study motivations. This is done in order to draw some conclusions on the nature of concept studies and clarify the nature of Requirement Elucidation. The studies were largely motivated by specific and real world requirement investigations, covering a wide range of roles, types and configurations. They all employ the DBB approach which utilises the ability of the Graphics Research Corporation Limited’s tool PARAMARINE-SURFCON’s to realise the DBB approach [24].

4.1 LITTORAL COMBATANT SHIP

This study for the US Navy was the example drawn on to illustrate the process steps in the DBB approach in Table 2. While this example of a naval ship concept study was an extensive study, it could be said to be somewhat untypical of an early concept study, in that the requirement was spelt out in some detail by the US Navy (see details in Reference 17). Rather the study was more of an investigation as to whether the PARAMARINE-SURFCON tool could be used to produce “believable” designs and, in particular, could do so for unconventional solutions, such as the trimaran example produced by the UCL DRC. The requirements of the US Navy’s Littoral Combatant Ship were accessed from open information [25] and the fast (40 knot) trimaran configuration option was adopted. The use of the DBB approach revealed the advantage of a trimaran configuration, with its large box structure, able to accommodate defined watercraft assets that would otherwise have to be accommodated less effectively in a narrower single hull. The other arrangement feature shown in Figure 5 is that the aft part of the main hull is dominated by the four shafts for the waterjets, which have to be accommodated at the stern along with the watercraft deployment ramp. The combination of the propulsive powers required and the

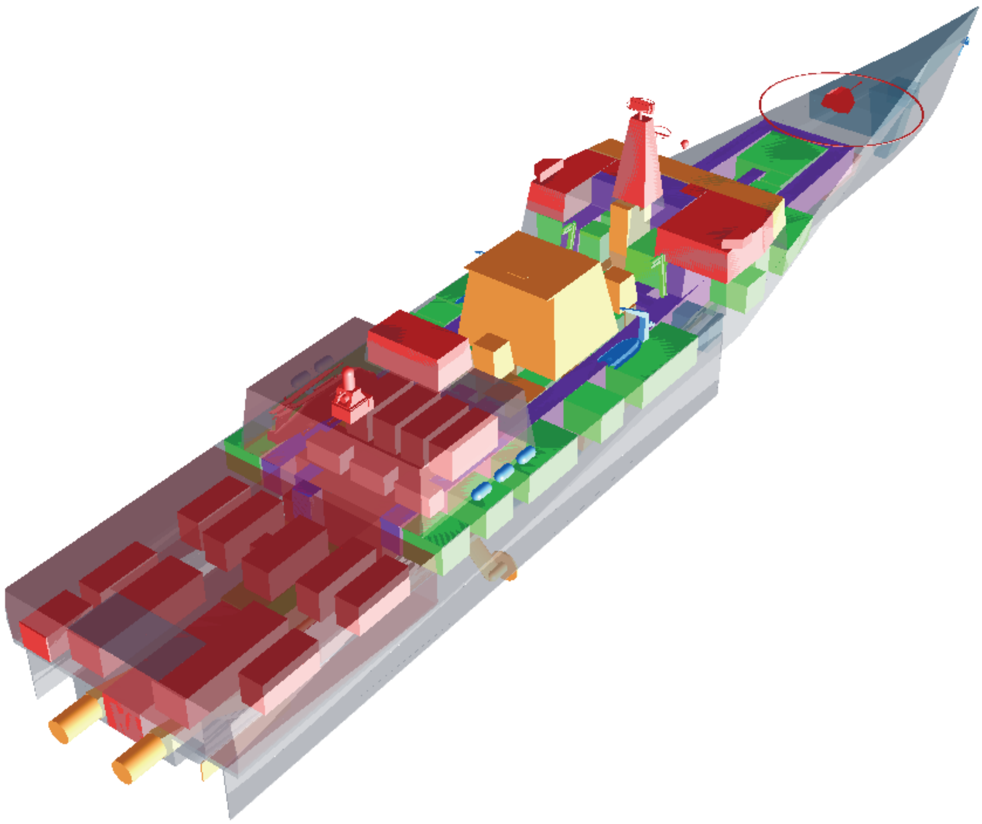

Figure 5: The SURFCON representation of the stern arrangements of the High Speed Adaptable Combatant Study [17]

need to stow and deploy, from the vessel's stern, several modularised assets made the design configurationally demanding, as can be seen from Figure 5. Without recourse to a full graphical representation in combination with the naval architectural analysis, using the PARAMARINE analysis modules, it is doubted if a believable concept design could have been readily produced for such an advanced configuration [17]. As such this is a good demonstration of how design insights can provide time, cost and risk inputs to the requirement formulation (see the first bubble of Figure 2) as a demonstration of Requirements Elucidation.

4.2 UK MOTHERSHIP STUDIES

The UCL DRC used the PARAMARINE-SURFCON tool to produce, in conjunction with BMT Defence Services, a series of novel ship concepts [26]. These were distinctly different ship configurations to meet the same operational concept of a fast "mothership" to transport over long distances relatively small naval combatants, which could then be deployed in a littoral environment, thus avoiding the need to deploy large and costly ocean going combatants. Each of the "mothership" configurations addressed a different deployment and recovery method, namely, well dock, heavy lift, crane, stern ramp and stern gantry. The study is comprehensively described in Reference 26 and so, for the purposes of this review, what is relevant is that the outline requirement was the same for all the designs (albeit much less well defined than the previous LCS example), so the point of this set of studies was to propose and investigate possible mothership lift and deployment configurations. It is relevant that such a set of naval architecturally balanced "motherships" design studies could not be investigated to such a level of design fidelity without using an architecturally driven design approach. This can be appreciated from the illustrations, shown in Figure 6, of the six vessel types produced and their summary design characteristics, provided in Table 3. Such a new ship concept is driven by not just the carriage and deployment of the small combatants but also, in most instances, the large water ballasting arrangements required and the considerable stowage capacity for the fuel, necessary to propel the vessel at relatively high speed (26 knots) some 10,000 nmiles. It was found that the architecturally based approach gave a higher degree of confidence in the realism of each of the distinct solution types. In particular the integrated representation of ship architecture and naval architecture mitigated against errors in the modelling, particularly in the interface between the spatial and numerical representations. Without such concept studies, such errors would not be revealed until much later in any subsequent design development when they might then be shown as rendering the specific configuration unworkable. Again this is an example of early stage concept exploration, which maintained an open investigation on a broad design concept, so exemplifying the difference between Requirements Elucidation and Requirements Engineering.

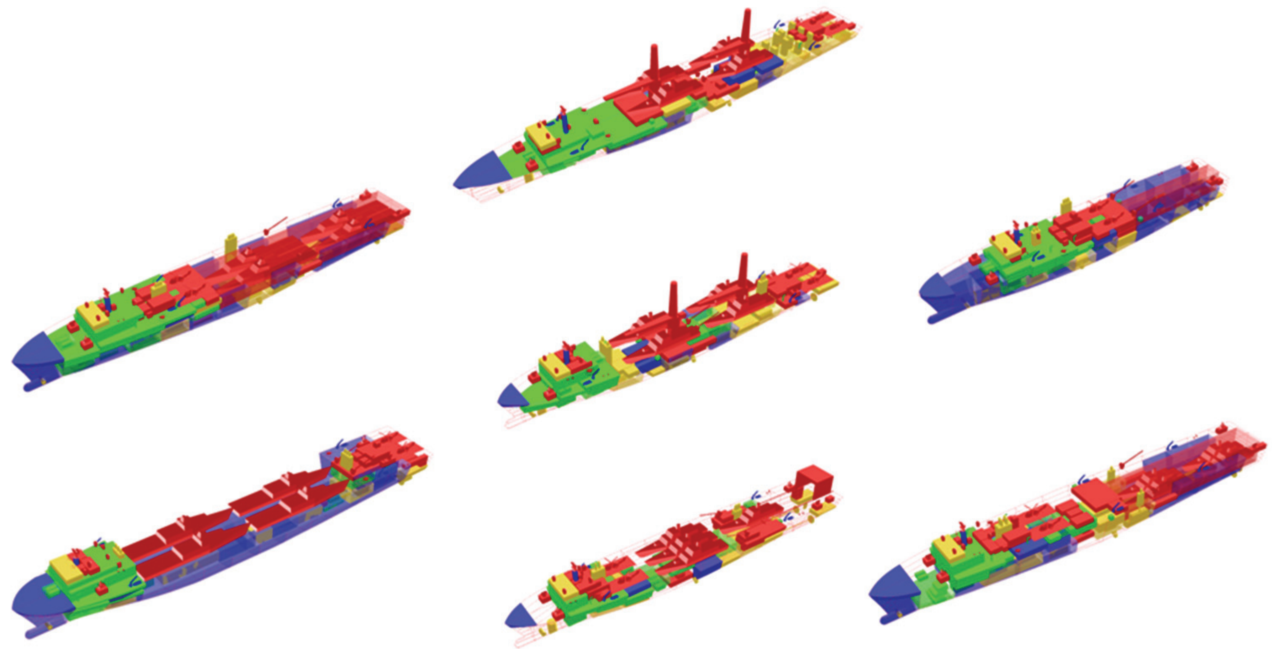

Figure 6: The set of Mothership ship options [26]

Table 3: Comparison of particulars for the set of Mothership options [26]

Study	Length, wl	Beam, wl	Draught, Deep	Displ, Deep	Ballast	Speed	Range	Accom.	Relative UPC
	m	m	m	te	te	knots	nm		
Dock Ship	250	31	7.2	32000	25100	18/25	10000/18	368	1
Command Variant	250	31	7.2	32200	25100	18/25	10000/18	368	1.04
Support Variant	255	31	7.15	34000	27000	18/25	10000/18	412	1.07
Heavy Lift Ship	250	35	8.1	38000	49300	18/25	10000/18	368	1.13
Crane Ship	220	29	7.3	25500	4000	18/25	10000/18	257	0.91
Fast Crane Ship	270	30.8	8.8	46200	6900	40	10000/40	257	1.72
Gantry Ship	220	29	7.3	25500	1650	18/25	10000/18	247	0.9
Deep Draught Ship	250	31.6	94	45700	18800	18/25	10000/18	247	0.97
SSK Dock Ship	190	26	6.8	20650	35500	18/25	10000/18	172	0.74

4.3 INNOVATIVE OPV STUDIES

This set of studies was another quick investigation as part of a more extensive concept phase and is described in detail in Reference 27. Again the broad ship concept requirement was spelt out for the study and could therefore be seen as part of an exploration of different hull configurations to show which of them might bring distinct advantages. The key feature of the operational concept was a modular payload stowage and deployment of a range of Unmanned Vehicles (UXVs) and how hull configurations, markedly different from the usual naval Offshore Patrol Vessel (OPV), might facilitate this. Three hull types were considered: a relatively conventional monohull but based on a commercial offshore support vessel; a novel broad transom design; and a medium speed trimaran ship. This set of studies could also be looked on as a discrete investigation to identify whether less conventional ship configurations might provide advantages in meeting a new operational concept. Figure 7 shows the three configurations, focusing on the key features of the modular stowage and the means of deploying the assets. Again the use of the DBB approach to explore a physical arrangement as a key driver of a balanced concept design, shows how the architectural element contributes significantly, alongside the technical balance, in enabling the Requirements Elucidation process.

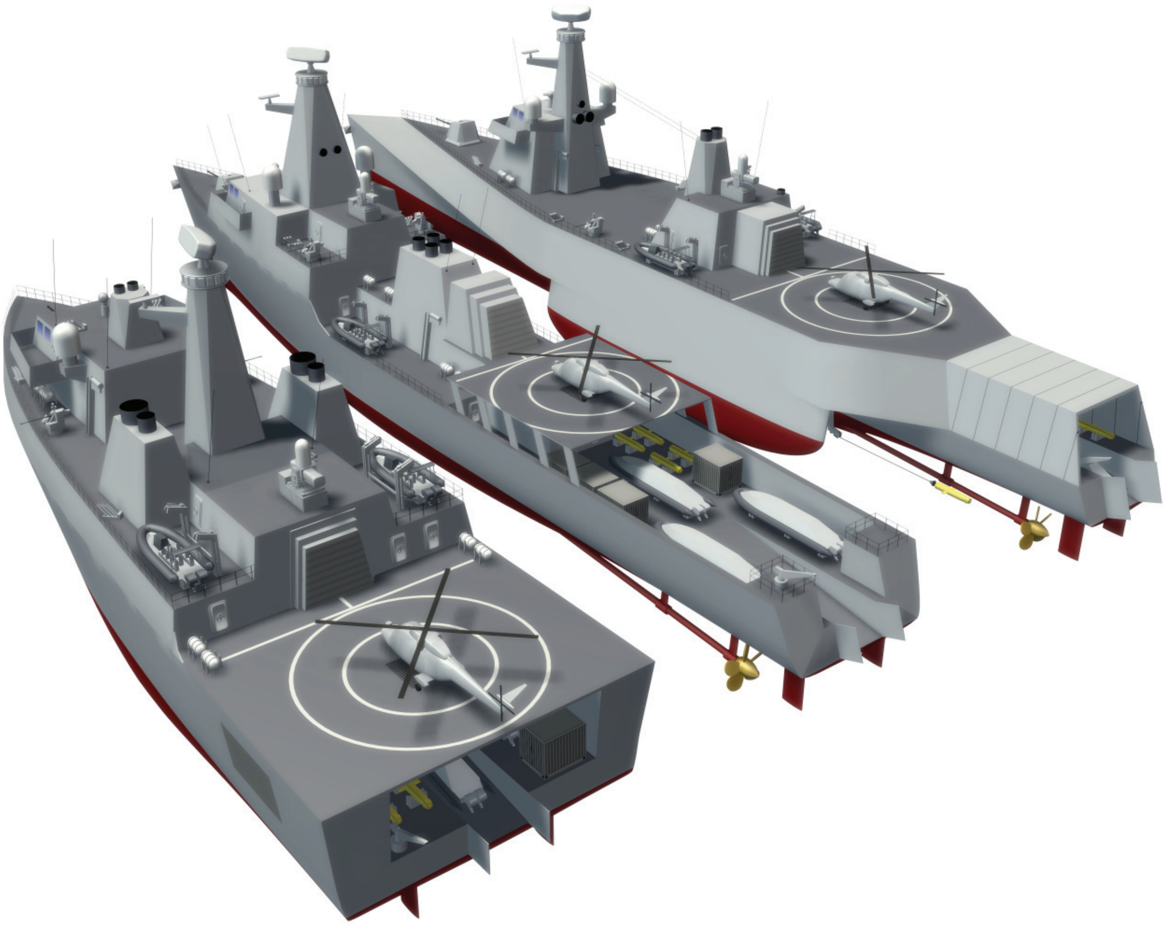

Figure 7: Visual comparison of three ship configurations of an OPV modular payload arrangement [27]

4.4 JOINT SUPPORT SHIP

This design work was undertaken by the UCL DRC, as part of a bid team responding to the Canadian National Defence Department's requirement for feasibility studies into a "Joint Support Ship" programme for a vessel combining logistics support, to the fleet at sea, with the capability to provide sea lift deployment of vehicles, to support expeditionary or humanitarian tasks. The UCL DRC task consisted of designing a range of possible design options, to investigate the impact of the many JSS capabilities on the configuration of this innovative concept. Each study was designed using the PARAMARINE-SURFCON system. Figure 8 shows the profiles of, firstly, four options, then two refined studies, followed by one (final) design, the latter being worked up in some detail with regard to the performance characteristics [28]. The issue to note is that, within essentially one ship form, the first iteration produced four distinctly different internal layout arrangements, able to be arranged using the DBB capability of the SURFCON CAD module. This again exemplifies the virtue of the architecturally driven DBB approach, such that the architecture was seen to drive the design evolution and hence the styles of the options could be compared. Thus it was possible to advise the bid team that the final configuration they presented had emerged from a full consideration of possible major layout variants, an aspect not usually able to be explored until a sizing and hullform had been broadly fixed. Without such an exploration any dialogue on the emergent requirements would have been limited to one basic configuration, potentially closing off variant solutions and their potential insights into the derivation of the requirements.

4.5 EARLY STAGE TECHNOLOGY IMPACT STUDIES

The previous four studies were undertaken in support of wider ship concept investigations to inform the dialogue in Requirement Elucidation, however another element in the early use of ship design capability is to look at the whole ship impact of actual or potential technological advances. Two such DRC impact studies were, firstly, that of an all-electric approach to combatant design [29] and, secondly, of prospective integrated electric weapons [30]. The first was undertaken on a typical Air Defence Destroyer design concept and consisted of identifying the whole ship impact of progressively more "all-electric" installations. Thus six separate designs were produced, one of which is shown in Figure 9, and they focused on the machinery spaces, within an overall balanced whole ship design.

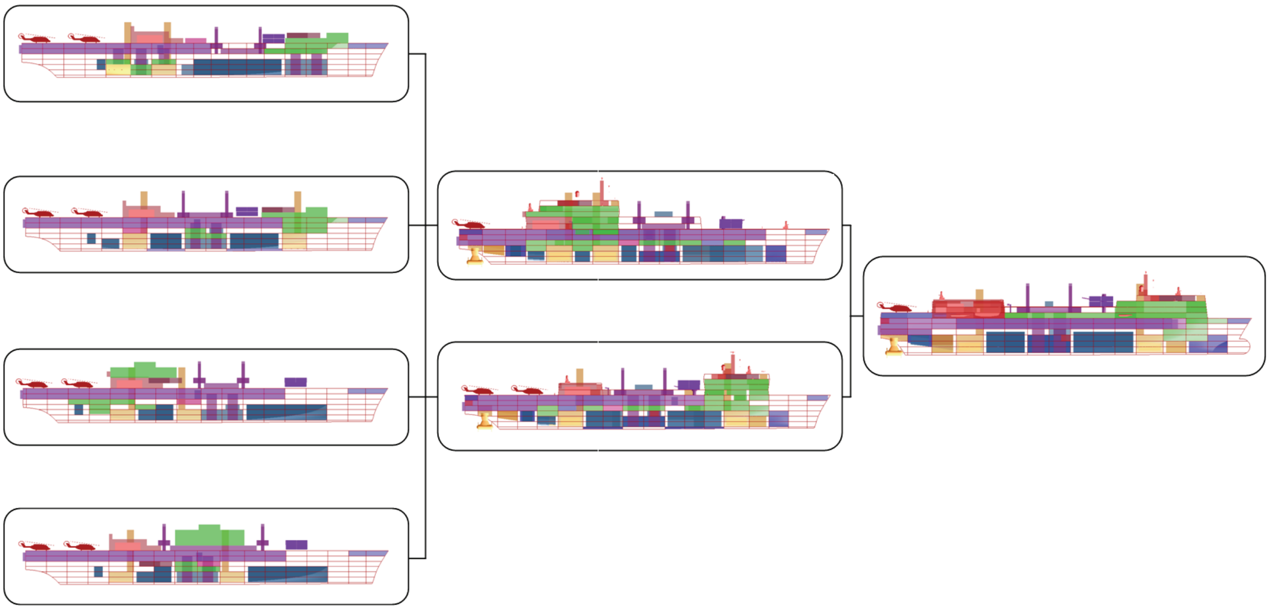

Figure 8: The sequence of JSS configuration options [28]

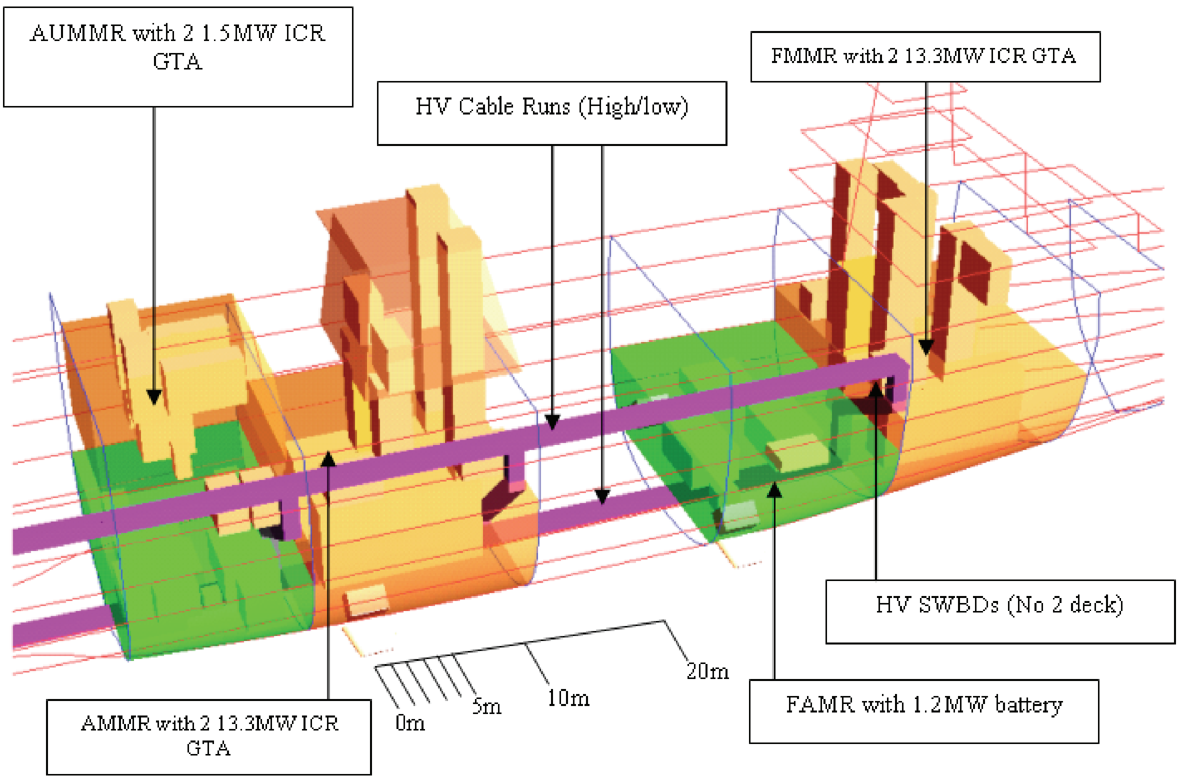

Figure 9: An example design in the set of destroyer designs on adoption of full electric power [29]

The second study looked, far more speculatively, at future laser and rail gun installations in a future Air Defence Destroyer and Figure 10, from Reference 30, highlights the fit of the "Fight" DBBs into a balanced ship design. Such studies can be seen as a way of informing a major navy of the consequences of new technologies. Thus both the specific technological development can be assessed, for its wider cost impact, and any associated ship research and development programmes can be justified, initiated and directed to tackle broader issues. Without such early ship impact considerations the latter are unlikely to be appreciated until potentially too late, leading to the need for expensive design changes in service. These two sets of studies were less part of a specific new programme's requirement elucidation than showing how ship impact research could be initiated and risk reduced, and so is still seen as consistent with the first "bubble" of Figure 2.

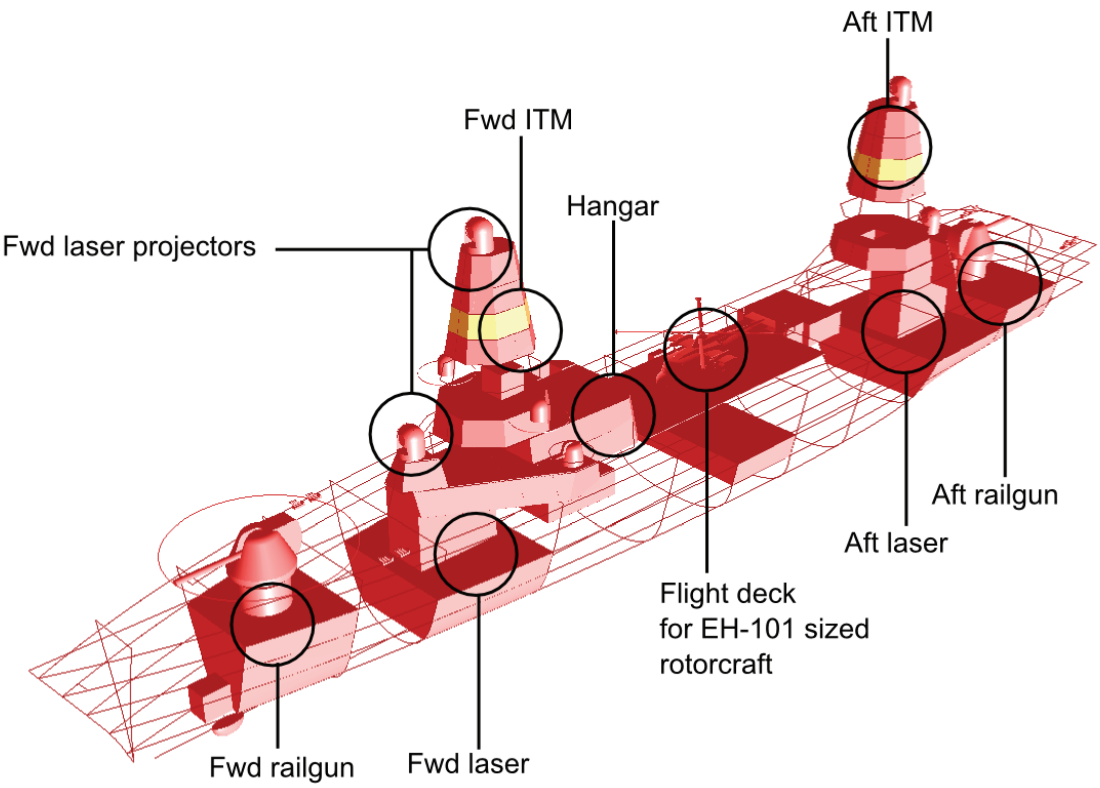

Figure 10: Fight Functional Group DBBs in the UCL Indicative Electric Weapon Destroyer [30]

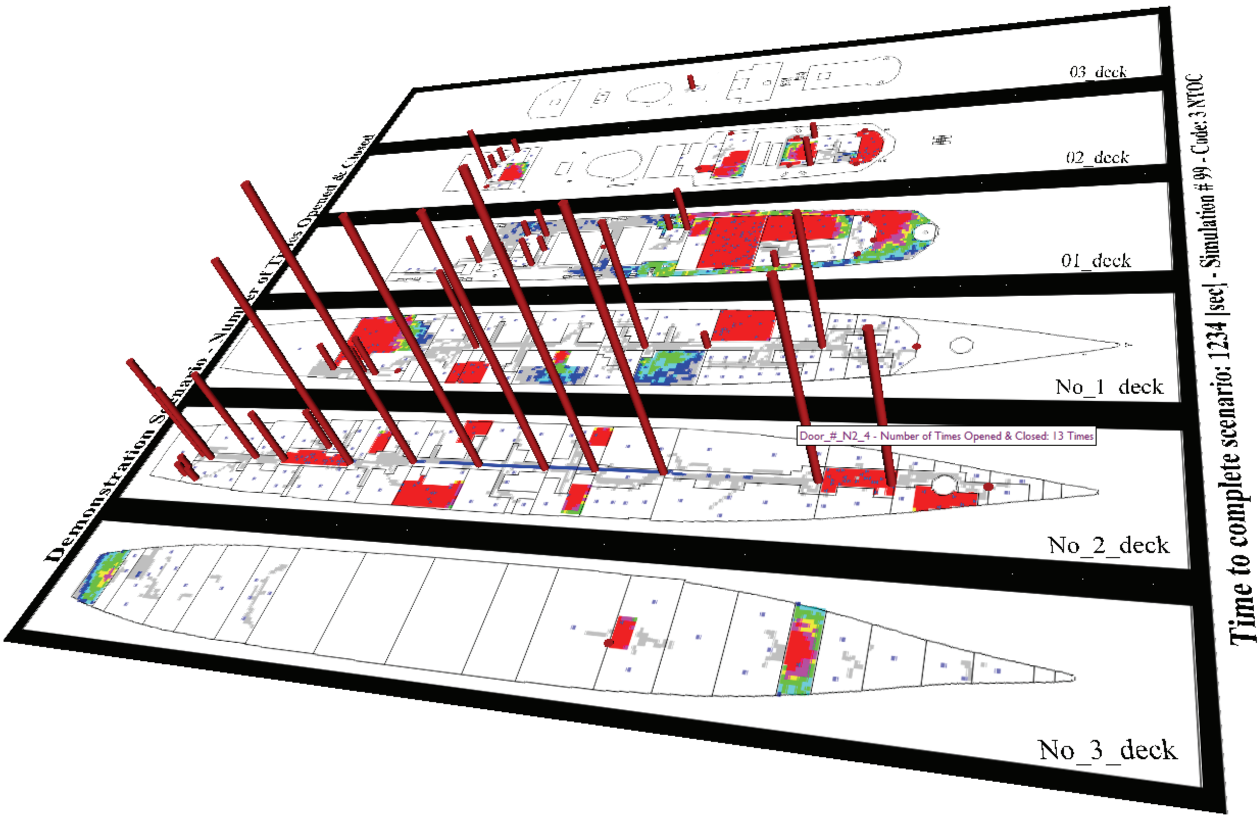

Figure 11: UCL developed interactive visualisation of a representative personnel movement simulation for a frigate design [35]

4.6 INVESTIGATIONS INTO EARLY STAGE INCORPORATION OF SIMULATION TOOLS

Due to the architectural dimension of the DBB based concept studies, a further set of initial design studies can now be contemplated. These studies address a wider range of issues than the traditional naval architectural topics. Thus issues like Design for Production [31], fire simulation [32], heat distribution [33], vulnerability [34] and personnel movement [35] can be modelled and simulated in early stage ship concept studies to see how new ship concepts and future requirements could be affected by issues traditionally not addressable in the concept phase. Of all the topics investigated by the DRC the one that has been considered in most detail, as a case study in the integration of simulation tools in initial design, has been that of personnel movement. While there remain considerable challenges to be tackled, to ensure that the ship design definitions and simulation derived data are kept to a level that is commensurate with rapid trade off needs at the concept stage, it is clear that the Requirement Elucidation dialogue can both be improved and more stakeholders directly involved in it by integrating such tools into concept design. Thus Figure 11 shows a typical display of personnel movement simulation results for a scenario of personnel movement on a frigate. Such a design representation could then assist in early design decisions on ship layout and complementing numbers. These simulation-based investigations, when combined with a DBB approach to concept design studies, importantly add a further dimension to the Requirement Elucidation process. They enable the ship designer to investigate aspects previously only considered, if at all, much later in a design and even then, typically, well after ship construction has commenced. Current practice means late investigations are unlikely to substantially influence the major requirements and design decisions, whereas the DBB approach can facilitate early effective consideration.

4.7 INITIAL CONCLUSIONS ON CONCEPT STUDIES

The range of concept studies briefly outlined in the previous sub-sections enable some conclusions to be drawn, in providing the ship design input to Requirements Elucidation, with regard to the comparison between the traditional concept sizing process (see Figure 4) and the architecturally based DBB approach (see Table 2). Firstly, there is a wide range of studies possible at the early stages of ship design and that range is increasing, due in part to the insights possible with an integrated architectural approach. Secondly, given the decisions that are made at the early (concept) phase are the most crucial, it is necessary that they be made with as good an exploration, as is possible and appropriate, of what might be the crucial issues. Traditionally, for the ubiquitous naval combatant, these issues have been "payload" dominated, that is to say they are focused on the major combat system sub-systems and specific equipment items. To a degree the traditional sizing process reflected that, however more technically significant to the naval architect, in particular, has been the dichotomy of achieving adequate ship stability with minimum hydrodynamic resistance at full speed. This is a clear indication, even before any of the wider design issues opened up by the integrated architectural synthesis approach are addressed, that such issues largely determine the overall ship design. Such "style" related aspects, rather than just the combat system, are often the drivers on ship size and its proportion of overall cost. Thus the S^5 issues (Speed, Stability, Seakeeping, Strength, and Style [36]) need to be addressed in the concept phase through the dialogue that is the Requirement Elucidation process. Aside from demolishing the false vision of "Platform vs Payload", which the Requirement Engineering misapprehension has fostered, this more whole ship vision also emphasises the importance of tackling the Style aspects, as part of the concept process. This now possible given the tools and techniques as is shown by some of the above architecturally driven design studies, where the results can be used to reassess putative requirements (see Figure 3).

5. THE NATURE OF THE CONCEPT DESIGN PROCESS FOR NAVAL VESSELS

From the above consideration of the process at the initial (concept) phase of ship design, there are seen to be five highly interrelated aspects. These then characterise this fundamentally different part of the process of designing such physically large and complex systems as naval vessels.

Firstly, the process is that of a wicked problem, as first coined by Rittel and Webber [7]. Unlike the downstream process, which is of a highly convergent nature and seen to be "pealing off the layers of an onion" to reveal more physical detail to gain technical assurance together with providing sufficient detail to manufacture the eventual ship, this phase consists of working out what is really wanted and what can be afforded (see Figure 2). It is characterised by starting with a (or even better several) blank sheet of paper to gain insight, in the form suggested by the first "bubble" of Figure 2.

Next, it is the key phase in the whole design process where the major decisions are made. Design has been characterised as decision-making in its entirety but, as indicated by Figure 3, the crucial decisions for the overall ship design process are made at the very front of the process. Many of these are often not appreciated by the two key players in the initial design phase – the requirement owner (usually the naval staff) and the concept ship designer. This lack of awareness of the extent of the crucial decisions being made can narrow down the options for consideration and arbitrarily constrain the task of tackling the, essentially, wicked problem.

Thirdly, decisions have to be made in coming to the conclusion of this largely divergent and exploratory phase, to then proceed into "engineering design proper". These normally consist of which one, or possibly two, outline design concepts, balanced to the limited extent appropriate to inform these early decisions, are to be taken forward. This is classically a "trade-off" process, where distinctly different options have to be assessed, despite their inevitably different attributes and levels of uncertainty. There are tools available to assist in decision-making but there is a risk in using them blindly, especially if the process has not been recognised as "wicked" and full of (potentially) unappreciated constraints. So there is the need to ensure that a comprehensive and challenging concept design process is being conducted. This has to be done before trade-off studies are undertaken and is essential to inform any quantitative trade-off process. Furthermore, such numerical trade-off studies should be primarily undertaken to provide enlightenment rather than being the sole basis of decision-making, since this can too readily be reduced to just ship cost arguments.

Part of the nature of this wicked, decision-making and complex trade off process is that choices have inevitably been made as to the "style" of the various design concepts investigated. Thus the next crucial aspect is identification of style. What importantly this does, in the concept phase, is to bring to the fore many issues, which are of major concern to the ship operator. These were either hard to recognise in the traditionally narrow concept exploration, or not considered addressable by the traditional naval architectural input to concept design studies. In what has been argued is a paradigm shift due to advances in computer graphics [22, 17], 'softer' design concerns, especially those dealing with the human factors aspects of PL&C systems, can now be readily addressed in ship concept studies – as examples in the previous section indicate.

The final aspect, not surprisingly, is that of Requirement Elucidation, which brings together much of the first four considerations but strongly emphasises that this first phase of design is not about a blinkered rush into the subsequent design phases but, rather, is a process of elucidating what is required. Furthermore, requirements elucidation can only be done properly through a dialogue between the naval staff and the concept ship designer. This needs to be open and un-constrained so both participants help the other in the decision-making necessary to cope with the wicked nature of the process. That the process must be done in a manner that uses the design skills of the ship designer should be all too obvious. Furthermore, ship concept designers have an obligation in this dialogue to encompass the exploration of style issues, many of which are beyond their (S^4) comfort zone and this is seen as a significant consequence of the paradigm shift. This consideration then leads on to a final set of statements as to what must characterise the output from concept design tools, if they are to assist the ship designer, in the complex acquisition environment for naval vessels, to properly undertake requirements elucidation:

- Believable solutions, that is to say solutions which are both technically balanced and sufficiently descriptive;
- Coherent solutions, which mean that the dialogue with the customer and other stakeholders should be more than merely a focus on numerical measures of performance and cost, by including a comprehensive visual representation (noting that SURFCON provides considerably more than an artist's impression of the outside of the ship);
- Open methods, in other words the opposite of a 'black box' or a rigid/mechanistic decision system, so that the description is responsive to those issues that matter to the customer, or are capable of being elucidated by the designer from customer/user teams;
- Revelatory insights, in particular identifying likely design drivers, early in the design process, to aid design exploration in initial design and beyond;
- A creative approach, not just as a "clear box" but actually encouraging "outside the envelope" radical solutions and a wide design and requirement exploration to push the requirement elucidation boundaries.

All this is consistent with the message of what is needed for effective requirement elucidation.

6. CONCLUSIONS

The conclusion of this paper is that Requirements Engineering with a sequential and non-material specific set of outputs is poor systems engineering. Rather Requirement Elucidation, as spelt out with reference to actual concept studies, is the correct aim of the front end process of acquiring Physically Large and Complex Systems, typified by naval vessels. It is recognised that this means the pre-feasibility design phase of such systems is not straight forward and will require further development in methods, tools and designer capabilities. Furthermore, only this requirements elucidation mind set is seen to provide a basis for improving ship acquisition in the demanding times ahead.

7. ACKNOWLEDGEMENTS

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