DISCUSSION

MARINE REQUIREMENTS ELUCIDATION AND THE NATURE OF PRELIMINARY SHIP DESIGN

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COMMENT

Mr C V Betts, FREng, RCNC, UK (Fellow)

My thanks to the author for a fine paper. It is also an important one, at least in the area of naval whole ship procurement where the idea of 'Requirements Engineering' has been taken up by those ignorant of the process of successful ship design. It is notable that such mistakes do not appear to be made in commercial ship procurement, where the pressures of finance, time and more direct accountability seem to concentrate the mind against ill-thought-out fads.

To be fair, while certainly not justifying the mistake, it may be that part of the reason for the over-abstracting of the requirements elucidation process was the desire to avoid a much older and, to some extent, opposite tendency. This was when both the Naval Staff and warship designers based both new requirements and new designs closely on previous designs, with little 'divergent' thought about alternatives that might better meet the overall need. That tendency was seen as acceptable when new classes of vessel followed one another rapidly but is less justified when there are, as today, long gaps in the design and production of new classes.

The new problem largely arises, as the author says, from the over-enthusiastic application of a type of 'purist' systems engineering. I totally agree with the author's argument that systems engineering is a very useful tool in naval vessel design but it must not be seen as a replacement discipline to the whole design process. Such a misjudgement appeared to be made by a prime contractor on a major recent project and I have little doubt that it was a major contributor to years of delay and a huge cost over-run.

We need to rapidly achieve a sensible middle way and the author's paper is an excellent demonstration of how to do that. It should be mandatory reading for all new naval designers, in both MOD and in prime contractor design offices, and in particular for those in the Defence Staff with the task of sponsoring new requirements.

Dr M Purshouse, FREng, Thales UK Ltd, UK

Whatever the prevailing view at the dawn of the 'Smart Procurement' era, mainstream opinion in Systems Engineering today would not challenge David Andrews' assertion that system requirements can only sensibly be set in an iterative Requirements Elucidation process which involves the concept designer as an active participant.

It is now widely recognised that requirements make sense only when set within an architectural context, express or implied, and the concept designer's trial solutions provide that context. Moreover, requirements cannot in themselves be costed; neither can time to delivery be estimated. Cost and schedule estimates must relate to potentially realisable solutions. This is true of all systems, software-intensive electronic systems included, for they can neither be costed, nor schedule estimates derived, on the basis of a set of requirements alone. The software architecture must first be established in a design process before parametric estimating techniques (lines of code, etc.) can be brought into play.

I agree with his conclusion that there should be a reference solution, at the appropriate level of detail, with every requirement set presented at Initial Gate. Is this really so controversial?

A further point raised by Professor Andrews is: are warships so different from other complex systems as to put them outside the Systems Engineering mainstream? I would argue that they are not: only, that there is a division of labour of to be settled between the Chief Systems Engineer (a role ushered in by the new discipline of Systems Engineering) and the Chief Naval Architect (a longer established role, evolved over time).

There is no denying the vaulting ambition of Systems Engineering which, according to the latest INCOSE definition:

"... is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Manufacturing, Test, Performance, Training & Support, Operations, Cost & Schedule and Disposal.

Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs."

As a subject, Systems Engineering has evolved to tackle the sheer complexity of today's systems that would defeat the informal methods used by polymath Chief Engineers in times past. Given that teams of people are involved, process issues are prominent and the focus is technical. This is not “project management” as such. That, in the UK at least, is generally understood to be the overarching process of managing a project to completion, within agreed parameters for performance, cost and schedule.

On the System Engineer view, naval architecture is one of the “discipline and speciality groups” which contribute to this effort. Some naval architects may take exception to this interpretation of their role, and who can blame them? For naval architecture has long been implementing some of the techniques which, according to current System Engineer thinking, are the responsibility of the Chief Systems Engineer. Examples include the conduct of Trade Studies to evaluate different whole-ship design options, and managing transversals such as safety, environmental, survivability, security etc. But, Systems Engineering aspires to go beyond this by including, for example, the combat system within the common approach envelope (not merely treating it as a “payload”), and indeed other topics listed above so as to be completely holistic in its approach. Having someone with overall responsibility for the entire solution promotes consistency and coherence across a project team, and is attractive from the customer’s perspective. For these reasons I believe that the Chief Systems Engineer role is here to stay.

The individual appointed to this role on any given programme would be well advised, however, to recognise his “parvenu” status, and agree with the Chief Naval Architect which of his whole-ship responsibilities (on the System Engineer view) are to be undertaken by the naval architecture team. This would certainly include responsibility for physical integration at the whole ship level, and many other duties traditionally seen as part of naval architecture.

The optimum “division of labour” between these two key individuals merits a proper study, for while the skills and experience of the individuals available in specific cases will doubtless have a bearing on the organisational arrangements chosen, some broad conclusions could be drawn. There are now several examples of how different projects have tackled the issue, and some have been more successful than others.

The Chief Systems Engineer must ensure that, below a necessary level of imposed top-level process and documentation uniformity, individual teams are free to use to use whatever design techniques and methods of solution representation are most appropriate to their domain. Requirements & specifications may be expressible in a standard format, but ways of representing solutions tend to be highly domain-specific. Electronic system designers, for example, will work with functional, logical and physical views. It surely goes without saying that this “block diagram” approach would be a wholly inappropriate means of capturing the physical layout and “style” that are of such fundamental interest and importance to all stakeholders in the design of a complex warship.

Professor P J Gates RCNC, (Fellow)

The author must be congratulated on a paper that addresses a particularly important aspect of warship procurement.

Certainly in the context of complex electronic and software programmes, system engineering is often regarded as a separate discipline from domain specific disciplines in the same way as project management can be regarded as a separate discipline. It is essential that the domain disciplines have a good grounding of both these subjects not only to understand their strengths and their limitations but also to ensure that their processes are not pursued until they no longer add value.

Prof Andrews refers to Systems Engineering as a methodology (a set of methods), however it includes both processes (describing what is done) as well as methods (describing how they are done) linked to tools. The processes are described in EIA-632 [37] derived from electronic industry standards where systems engineering is used to ensure a systematic approach to data flows and system interactions. Despite its origin, EIA-632 is applicable to any engineering enterprise. It is especially appropriate for complex systems with high software and control functions in their subsystems. Several examples from a range of industries are quoted in the *Guide to the Systems Engineering Body of Knowledge* [38]. The design and development of warships has parallels with complex multi-disciplinary programmes termed Complex Product Systems (CoPS) [39]. Indeed, this term may be synonymous with PL&C systems in the paper. Such programmes are large, high cost, intensive high technology engineering activities producing unique operational products without full-scale prototypes. They comprise many, often customised, elements whereby small changes in one element can induce to large alterations in other parts of the system. Their nature is to have engineering challenges that can only be overcome by innovation and the development of new practices and equipment. Heathrow Terminal Five is a typical example [40]. Warships exhibit all the characteristics of CoPS as so many of their high technology elements can only be developed by using system engineering techniques. A comparison of CoPS programmes with warship programmes may be a fruitful area of research.

For warships the combat system, integrated electric propulsion systems, communication systems, bridge systems and integrated platform management systems generally use a systems engineering approach in their development because of the unyielding nature of their software and firmware. It is appropriate that all requirements of the warship are devolved to these systems so that their physical aspects and interactions can be systematically assured. Surely the question should not be "Is systems engineering appropriate for warships?" but "Given the widespread use of systems engineering in key sub-systems and integration, why is systems engineering NOT used for the whole ship?"

I applaud his use of the term Requirements Elucidation but fear that it may be confused with Requirements Elicitation that is already in systems engineering parlance and involves capturing source requirements. EIA-632 defines two requirements processes: Requirements definition and Requirements Analysis. The former involves performance analysis, trade studies, constraint evaluation and cost-benefit analysis. It entails elicitation of the requirements in relation to the operational requirements (military capability in the case of warships). It establishes the impact of system requirements on sub-systems and establishes the hierarchical allocation and traceability. Importantly, it is iterative and balances 'top-down' and 'bottom-up' aspects as the requirements are flowed down to sub-systems thereby providing an understanding of the interactions between the various functions so helping to form a balanced set of requirements. Requirements Analysis identifies & expresses verifiable requirements so links to the acceptance process. In fact the latest version of the INCOSE Handbook [41] merges these processes [42].

Of course the V-diagram shown in Figure 2 is based upon The STARTS guide [43]. Although originally for software this has subsequently been applied to a multitude of engineering and business enterprises. The key aspect often overlooked is that it describes processes not sequential stages like earlier true waterfall diagrams. It relies on feedback of each process to preceding ones as well as interaction between processes at the same level. All processes are active throughout the programme (although the emphasis and effort applied to individual processes varies as the programme progresses).

The practical application of the concept design and its outputs will be heavily dependent upon the acquisition strategy and the maturity of the potential constituent systems. Where many development items are involved the solution may not be 'non-material specific' but will have to accommodate a high degree of material uncertainty.

Whilst not specifically included in his research, I should like the author's comments on the example of the Type 45 destroyers. After two decades and at least six attempts to replace the Type 42 destroyers, the Ministry of Defence was able to place work with industry in late 1999. It quickly became evident that, as the Type 45 would be a test bed for several major systems for which no solution had been achieved. (It was subsequently estimated that 80% of the ship was new items, many of which involved cutting edge technology). The first of class entered service late and over-budget. Part of the reason was delays to Sea Viper (PAAMS), a programme over which the UK had little control and had already been identified as a risk. Indeed, in 1999 a senior civil servant had warned that the UK would be 'punished' for leaving the CNFG programme. It would be natural for the PAAMS Programme Office would place the needs of the French and Italian version of PAAMS ahead of those of the Type 45's Sea Viper version (that differed in many respects from the Franco-Italian version).

The Type 45 contract was based on nine Key User Requirements [44]. As the design developed the requirements were captured, decomposed and managed using a tool (now obsolete) called Cradle.

In evidence to the Public Accounts Committee (Q31 Supplement) [45], the Ministry of Defence stated that a lesson learnt was not to contract on such a performance-based specification but to rely on a solution-based specification. In practice, the requirement definition was probably not sufficiently mature to produce a meaningful solution-based specification for such an innovative warship until the project had completed several years of design, development, equipment testing and ship fabrication. KURs seemed to offer a useful starting point and not, in themselves, the source of difficulty. It would be unfortunate if a reaction to criticism were to abandon the benefits of the use of KURs instead of overcoming any shortcomings. Does Prof Andrews believe that a concept design for a ship can provide sufficient detail for a solution-based specification or is appropriate to develop requirements to a more detailed level than KUR before the exact solution is developed?

Since the Type 45 we have seen ship specifications for competition that have been re-written several times and are, as a consequence, inconsistent and incomplete as well as unnecessarily prescriptive as to the material solution. They do not easily admit the possibility of innovative approaches. It would be useful if the MoD were to use its own preferred requirements tool, Dynamic Object Oriented Requirements System (used in the design of QEC Class Carrier), for all warship acquisitions as a means of communicating requirements and to encourage innovation amongst the more enlightened contractors. This tool is a powerful way of ensuring that requirements are flowed down to sub-contractors in a consistent and traceable fashion. I would be interested in any views Prof. Andrews has on the integration of such tools with his Requirements Elucidation processes.

Professor A Ulfvarson, Chalmers University of Technology, Sweden

Thank you for a very interesting paper. The comprehensive overview of design methods in the paper is gratefully acknowledged. It reflects considerable experience from many design projects. After having discussed your paper at length with Mats Nordin, we concur on your conclusions but would like to add a few points to the discussion.

Requirement Elucidation is elaborated in a way that adds to the Systems Engineering vocabulary and definitions. To me, it is not a dramatic change from my interpretation of Requirement Management, probably because my understanding is that requirements need to be exposed and questioned interactively with the customers before they are set. And then they are never absolutely frozen: whenever I am uncertain of my understanding of requirements, System Engineering tells me to go back for clarification. It may not lead to changes. That is a matter of judgment, but it increases knowledge. Now, this process you describe has been given a good name of its own, which I think is good.

Since the type ship design was exhausted as a method and design practice evolved into the beginning of the 1990s, Sweden has shifted over to mission driven design. Requirement management was for a period applied in an unintended way, thus we had to deal with “requirement accountants”. These specialists, often officers from the naval staff, usually had no design or engineering training and seldom enough experience of the design process.

However, our intention was to focus on the operator’s needs. A proposed design solution should reflect these needs by delivering the best technical and architectural design within affordable cost restrictions: it should meet the naval staff’s system effect targets e.g. a certain level of result for each and every type of mission identified for the future ship/submarine.

Requirements are only valid if they can be realized in a design solution that is affordable and meets the identified or stated needs. To balance and find the best solution in a mission driven design process without operations analysis is in our opinion not effective, thus not the best use of systems engineering.

Before one can converge in to a certain part of the design space, i.e. the design room, one has to fully investigate and explore the design space. This includes not only technical design but also an evaluation of the related cost and effect. When this has been done in an iterative process the design team can find a balanced and reasonable good set of requirements, which meets the cost target for an accepted level of systems effect of different mission types. If not, the design team may suggest resetting the cost or reiterating the work. This is not only requirement elucidation but also requirement design – an iterative process between needs, design solution, cost and effect.

We often discuss how one should convince the reader of the results of our work in development of design. Is it an art or is it a science? This problem we all share with you. As an example I select your statement on page A-32: "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". I am thinking that you and your team members have been convinced by your experience. However, the reader is still dependent on your judgment rather than his own assessment of the proof. These things are difficult to set in a scientific paper. We have the same problem of finding an unambiguous line between observation and conclusion in these matters. The conclusions, which I fully agree with, are however supported in your paper by the logic of arguments and should be implemented in System Engineering design processes.

Dr J van Griethuysen, FREng, RCNC, MoD, UK (Fellow)

The paper is good but could be even better. It is very persuasive in showing how the architectural configuration and “Style” of a ship has a major impact on the eventual solution, how this needs to be brought into the design process early in order to influence the concept trade studies, and how concept tools like the Design Building Block can help in achieving that outcome. However, the paper could be improved by more formally showing how the style and configuration actually affects the Requirements rather than the Solution. The paper certainly shows how the solution is influenced but the central point of the paper is around Requirements Engineering. In this respect it does not quite nail the argument and give the evidence required. It could be quite possible for the Requirements to be a constant, but for configuration and “style” to result in a range of concept solutions (as illustrated in the paper). What the paper then needs to bring out is that the configuration chosen either:

- Demands new system requirements to be defined which are unique to that configuration (e.g. structural loading and seakeeping requirements).
- Encourages the user to take advantage of the benefits of a specific configuration, and therefore he can ask for capabilities which are easily provided or come for free – so there is variation in the requirements and they are no longer common across configurations.

I think this would be relatively easy to do and will not require any further studies. It would also be interesting if the author could discuss whether this feedback effect influences the User Requirement as well as the System Requirement.

Professor C B McKesson, University of New Orleans, USA

I applaud Professor Andrews' contribution. The earliest phase of ship design must be requirements elucidation, and requirements cannot be developed blind to their eventual realization in hardware.

Part of the blame for the current "mess" must be shouldered by we naval architects. We are too quick to home in on "the" ship, and are reluctant to envision a cloud of possible ships, with the preference for one or another member of the cloud shifting as the user's vision shifts and evolves.

This same problem underlies some debate in design tool development in which I myself have participated. I have been on advocate of a class of Very Simple Models [46, 47 & 48] which offer the ability to explore large design spaces at low fidelity. I have "opponents" who opine that even the very earliest design phases should be conducted at the highest possible fidelity. I believe that this difference of opinion is related to the difference between the early stage task of Requirements Elucidation vice the task of starting "the" selected design.

David's selected definition of a wicked problem is also of the same ilk: the "remaining steps of searching for a solution" are a lot more comfortable, and we hasten, too soon, into those steps and begin to design "the" ship.

I have adopted Professor Andrew's terminology, and in my course in ship design at the University of New Orleans I define the first stage of design as Requirements Elucidation; followed then by Feasibility, Preliminary, Contact, and Detail.

I thank Professor Andrews both for this useful term, but more importantly for the important dialogue he is trying to provoke in this series of papers.

In brief I say: Hear hear!

Professor A Brown, Virginia Polytechnic Institute and State University, USA

The process I started teaching when at MIT (20 years ago) begins with Concept and Requirements Exploration, followed by Concept Development. Today the USN calls C&RE an Analysis of Alternatives (AoA). Simply put, you cannot set requirements until you understand the relationship between effectiveness, cost and risk for your design/mission. I avoid the word requirement until Concept Development, although you will have constraints from the start. We (USN) begin C&RE with an Initial Capabilities Document; used to be a Mission Need Statement which I preferred. No mention of requirement! This takes discipline which we usually do not have. The first requirements document is in the Capability Development Document (CDD, used to be ORD) which comes after Concept Exploration, then Concept Development and Preliminary Design come after that. When you start from the beginning with a "requirement", cost and risk never are under control.

Mr N Cooper, FREng, JN Cooper & Partners Ltd, UK

Please don't believe that the issue of design by requirement, and finance is just a ship problem. It extends throughout all industry where I believe that the holistic multi skilled engineer is being side-lined and is becoming potentially an extinct being.

Too often common sense thinking with an understanding is being replaced by micro financial project management, that makes hopeful engineering guesses that can satisfy the budget but where no real understanding of the integrated engineering solution has truly been considered or understood. The problem being that the designer wants to design and as such has not become a financial manipulator. Why?

Engineering has become more and more specialised into discrete disciplines, with rigid boundaries. To resolve this pigeon holing, more and more management is being introduced, and integrated thinking is replaced by documents and requirement capture. The multi skilled holistic engineer with the ability to draw and undertake scoping calculations to demonstrate the viability of an option as they balance the finance with risks is rare.

The power of the old chief engineer has been replaced by the control of management systems. (My fear is that this approach towards engineering has made the UK uncompetitive and inefficient). To resolve the lack of integrated thinking we then have created new forms of engineering that may be required in the software industry, but was not required in the traditional engineering sector. Clients ask for a system engineer to ensure the designers integrate the work, Clients ask for Human factors engineer reports to ensure the designer remembers to consider how something is built. I'm not saying these sectors don't have a role, but it's as if the old joke of about 'how many people does it take to change a light bulb' is coming true.

How many people does it take to draw a beam?

1. CAD operator (Not the old draughtsman)
2. A stress engineer
3. A requirement capture manager
4. A consultant to advice on the bending moment.
5. A system engineer to ensure the overall solution fits the main GA
6. A human factors engineer to check it can be installed
7. A assurance manager to check a checker has been appointed
8. A governance manager to check that the assurance manager has applied the correct procedures in checking the checker.
9. A project manager to manage the 8 people.

By the time the beam is issued nobody had mentioned that the requirement should have been removed from the WBS because it was no longer required!?

We have lost the 'Sergeant Majors' of engineering (the old chief draughtsmen and chief Engineers people who felt engineering) and as such we must start getting our qualified engineers to start drawing doing scoping calculations and designing hopefully becoming the integrated design leaders of the future. What is a design leader he is the designer who is prepared to make a decision and send a project forwards after balancing:-

- What the client wants
- What are the possible options
- What are the risks
- What are the costs
- How long will it take?

This appears to be a rant; however this country requires more doers of engineering rather than management systems to control engineers. Trust, Empowerment, and Praise builds Engineers and gives confidence.

Professor A Finkelstein, FREng, University College London, UK

Thank you for this very interesting paper. I think it would be fascinating to bring together the software engineering and the ship design communities around the themes that are brought out here. I think it might be useful to compare the thinking in this paper with the 'think piece' from a former student of mine, Bashar Nuseibeh [49]. He discusses the weaving together of requirements and architecture (aka concept design) in the style I guess this paper is driving towards.

Dr C Elliott, FREng, Pitchill Consulting Ltd, UK

I'm the author of the RAEng document [12] so not surprisingly find much to agree with in this paper!

We still labour under the thinking encapsulated in the Defence Industrial Strategy, published back in 2005 and no longer policy but still present [50]. Page 59 has the following waterfall:

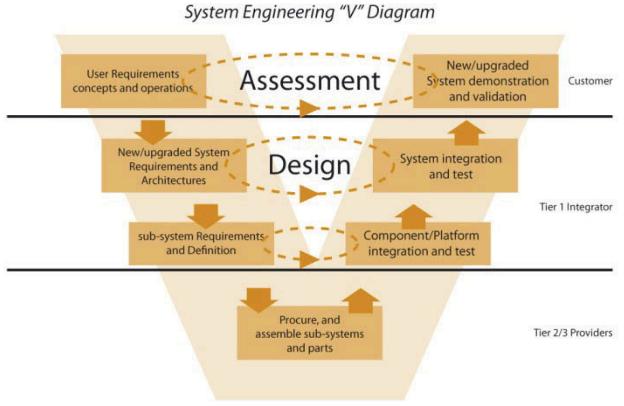

Figure 12. Waterfall diagram from Reference 12.

The critical stage that we are concerned with - reconciling what the customer wants, what the technology can deliver and what it will cost by when - appears in the top left above a line indicating that it is reserved for the customer. The Consultation Paper "Equipment, Support, and Technology for UK Defence and Security" published a year ago purposefully ignores the concept of partnership (other in cyber security) so implicitly excludes the kind of cooperation that we were advocating in the RAEng Guidance [12] and that David is advocating in this paper.

Mr R Skarda, Steller Systems Ltd, UK (Member)

I fully support the conclusions of the paper. I have many stories to tell of 'barking' conversations with requirements engineers, from my time in the Ministry of Defence, such as the one about "we want to be able to travel xxxx miles at 21 knots and have 50% fuel left", where xxxx was a very large number. This was driven by a capability requirement, with no context in the real world. When I asked for the context I pointed out to them that the 2 major routes to where they wanted to go went past 3 separate and available NATO fuelling points and I could get them there faster if they stopped to refuel!

There cannot be separation of the requirement and the environment (or architecture). I would say this is a wider problem than simply the architecture of the platform (I know you hate that word but bear with me). Unless you pull together the Defence Lines of Development into the concepting process and especially personnel, infrastructure and logistics, you miss many opportunities for a better through life and lower cost solution. You can only control this process well however with the really useful parts of Systems Engineering with the proper management of interfaces. These useful parts can be completed pragmatically as I have recently done for the MoD on a major armoured vehicle project.

Too many projects I have worked on have failed to manage the link between the entirely correct drive for an effect on the enemy and a solution that has a good handle on Performance, Cost and Time. This has been due partly in the UK to geography; requirements are written in London and sent down the M4 to Bristol. This cannot be the case as early on there is much trading to be done and understanding of the effects on the architecture.

Of course, all this means is that you have to start a little earlier, spend a bit more money up front to reduce the risk and we all know that governments love doing that! We have to advise them on the benefits of it though [51].

Professor P Wrobel, FREng, University College London, UK (Fellow)

Some thoughts based on a wide range on Naval Projects:

- Systems Engineering is one of the key process for the design, build and acceptance of complex ships;
- Like all processes it needs to be tailored to the project - too much is just as bad as too little;
- System Engineering evangelists are dangerous - just as all other process purists;
- System Engineering deniers should be retired;
- Textbook Systems Engineers are not an alternative to those who have delivered complex systems;
- Software Systems Engineering needs are quite different from those of complex ships i.e. significant tailoring is essential;
- The "V Chart" is very useful schematic - like the London Underground map. Like all schematic representations the reality between the key way points is complicated, iterative and multi-faceted. This is particularly so in the early creative phases. Unlike the London Underground the project does not run on fixed rails. As Chris Elliott says above “That's why the RAEng guidance [12] has a copy of the London Underground map on its cover”.

I endorse the comment about purists - there is a "Systems Taliban" who think that system engineering is just adopting the Unified Modelling Language (UML).

Professor A D Papanikolaou, National Technical University of Athens, Greece (Fellow)

The author's numerous papers on preliminary ship design approaches are masterpieces of our field and important tools in our ship design education. No need say much about this once more... Maybe, what could be stronger stressed is the big difference in setting-up the requirements of a naval and a merchant ship; thus, also, differences in the way of analysis of their requirements and the effect on the next steps of the design process. We have tried to elaborate this together with David in relevant State of Art reports of International Marine Design Conference (IMDC) [16, 52, 53 & 54]. Simplified models are always very valuable tools, both for ship design education and practical applications, assuming that we can trust them (and their uncertainty is manageable). In any case, we should not underestimate today's software power and the possibility to generate thousands of fairly detailed designs, if proper parametric models and relevant software are available.

Mr M Macdonald, BMT Defence Services Ltd, UK (Fellow)

This is a much-needed paper that rightly illuminates a fundamental issue in engineering today – the misinterpretation of the discipline of system engineering when applied to the most complex, indeed wicked, physically large projects.

I offer three main comments to reinforce the observations and conclusions. Like the author I am a naval architect who has worked in the UK Ministry of Defence, so there is a danger of too readily identifying with the paper. Therefore I offer first a view from the perspective of another engineering discipline in a paper that I rather like. I then discuss first-hand experience of the changing nature of engineering in the UK MoD, before introducing an approach that my company had developed.

In questioning its universal applicability, the author identifies the origins of system engineering in software development, to which it is very well suited. Looking at the discipline from a closer professional perspective, the discussion of systems engineering by an assistant professor of electrical and computer engineering at the University of Alabama as early as 1996, is a very refreshing assessment. Mark W Maier [55] questions the utility of systems engineering even to his own field. He argues the case for something more subtle which was emerging at the time and being called ‘system architecting’. To set the scene I quote from his abstract, *“Systems architecting applies the spirit of civil and naval architecture to complex, multi-disciplinary systems in aerospace, electronics, and information processing. The system architect is responsible for the beginning and end of a systems development cycle. The architect emphasizes blending of client needs and technical capabilities to outline a feasible system concept, following the heuristic ‘All the really important mistakes are made the first day’”.*

In his paper Maier firstly observes, *“Within the system engineering community, the conventional wisdom is that a rigorous and well defined development process is the key to success. The engineering process is a series of defined steps – analysis, requirements, design, implementation, deployment – followed in sequence in one or more development cycles. The general belief is that separation of steps and defined processes best ensure that customer needs are met and that design engineering proceeds with maximum freedom.”* Like Andrews, Maier is not content that this is relevant to complex systems and, in setting out the case for ‘architecting’, he shows that architects are subtly different from engineers. *“A tenet of architecting is that large scale success is related to a system design role analogous to the historical roles of civil and naval architects. The observation is that highly successful and breakthrough systems are guided by highly gifted individuals or small teams that perform initial conceptual design and maintain system integrity through to system acceptance. These ‘architects’ stand aside from the builder, act as intermediaries for clients, and their concerns range well beyond the specific engineering domains. Their process is built from the same elements as the conventional system engineering process, but is iconoclastically traversed with requirements, analysis, and high and low level design mixed together. The architect’s goal is to establish basic system* *requirements, but only to establish them when it is known that a feasible implementation exists whose characteristics represent a satisfactory compromise for the user."* That last sentence almost says it all. It is salutary to have one's own profession encapsulated by an electrical engineer so eloquently and efficiently.

Ironically Maier, some fifteen years ago, was looking to the sophistication of naval architects for a better model for his complex electronic system design, while today Andrews is suggesting that in the UK MoD at least, the naval architects have been looking in the reciprocal direction and making a mistake!

My own experience reinforces that of Andrews. I was one of those implementing the new policy of systems engineering in the MoD around 1999 to 2000 an offer a more self-critical view. To be brief yet blunt I oversimplify our difficulties under two headings. Firstly we had a new organisational structure that consciously made the military staffs have a more transactional relationship with the project teams. Yet, what should have been an intimate relationship of mutual learning and complex trade-off between the two parties (informed by concept designs) had instead a tendency to become a list of requirements 'thrown over the wall' to the project to get on and deliver the next serial stage – a solution. Secondly we did exactly as Andrews describes and lost the subtleties that do exist in the systems engineering model; we let it become a serial process to be applied almost without thinking. The whole was compounded by the fact that we were fast losing the skilled, experienced people who could cope with the complexity of trade-offs, of compromise, of difficult decisions, of the art of design or of architecture (or architecting). We were replacing people with process, finding comfort in an attractive, logical systems engineering approach yet not applying it as cleverly as we should. Before long we had very large databases full of exquisitely written requirements, neatly categorised and so on, yet it was rare to find concept designs that were informing the all-important trade-offs, the difficult decisions, the art of the possible.

Lastly, I'd offer an insight into the approach developed in the company in which I now work. We deal almost wholly in the physically large and complex, including ships, land vehicles and information systems. Our people cover a range of disciplines, including naval architects, software developers, and system engineers. Our approach is to promote learning between the disciplines, for example bring systems engineering into naval architecture and vice versa, without losing the skill (and art) of each. To counter the misinterpretation of Systems engineering as a who;;y serial activity, we have replaced the traditional 'V diagram' with what we call the 'O diagram', described here by Stu Olden [56].

The 'O diagram' is different in two important ways. It explicitly introduces a feedback loop of review and learning across the top; and it explicitly recognises the iterative nature of the earliest activity. This early activity we call optioneering, iterating between the architecture of a solution and the requirements it achieves. Importantly the ultimate requirements are the result of this optioneering and provide the input to detailed design. In BMT Defence Services, this is the approach we take not just for ships but to a range of design problems.

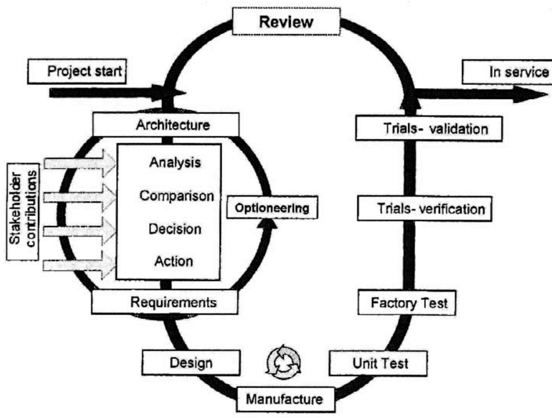

Figure 13. 'O diagram@ from Reference 56.

In conclusion I see Andrews', Maier's and Olden's contribution being fundamental reminders that the engineering of the physically large and complex is as much an art as it is a science; it does not have a single, deterministic solution; its success (or failure) is rooted in the earliest activity of exploring requirements; and it is much more about the right people than it is about the right process.

AUTHORS' RESPONSE

I would like to thank all the contributors that responded to the invitation to comment on the paper. Rather than answer each contributor in turn I have grouped both the comments and my response to each of these under three main headings as I think this will be more informative to the general reader. The main headings are:-

a. major issues raised by the five substantive set of comments on the argument in the original paper;
b. comments addressing specific points;
c. comments that address the general nature of systems engineering.

1. MAJOR COMMENTS

Mr Betts, as an eminent naval constructor, while strongly supporting the author's critique, wondered whether there was some mitigating excuse in the adoption of Requirement Engineering in recent years. In this regard Requirements Engineering could be seen as an over-reaction to historical procurement practice, where new requirements and new designs seemed to have lacked much divergent thought. This over-reaction seems less justified with today's longer gaps in the design and production of new classes. – I would respond that with greater time gaps in acquiring major projects the approach that seems to have been adopted is not to adopt divergent thought but to use rigid Requirement Statements to artificially constrain the eventual solutions.

Mr Betts therefore concluded that there is a need for a sensible middle way between 'Purist' systems engineering stance, where SE is seen as a replacement design discipline, and the previous practice in ship design where the naval architect led the design. He argues this middle way could be provided by the approach propounded in the paper, which he considers should be mandatory reading for designers and Defence Staff. - I would clearly endorse that suggestion, however the issue then becomes that as to how the (naval) defence staff can be meaningfully engaged, as there seems to be a breakdown in that regard.

Dr Purshouse, as a distinguished systems engineer, sees the need for a reference design at Initial Gate being uncontroversial. – This, however, seems to highlight a misunderstanding, in that the object of Requirement Elucidation is not the production at the end of concept of a "reference design" but the need for the ship designer to be intimately involved in the whole requirement evolution from the start. Namely to have the informed dialogue with the requirements owner to tackle the "wicked problem". The reference design could then emerge as the outcome of that dialogue providing a much better measure, at the first major decision point, of what is achievable and affordable, rather than being the designers' response to an apparently firm set of requirements.

More controversial is Dr Purshouse's espousal of the Chief Systems Engineer as the wider project coordinator – This role has been historically taken in naval ship design by the naval constructor as "the first amongst equals". Warship projects still seem to have a naval architect as Design Manager (US Navy practice is to call them, initially, Ship Concept Managers and then, downstream, Ship Design Managers [19]), but there remains an argument as to whether Warship Project Managers (or warship Integrated Project Team Leaders (IPTLs) should also be naval architects. It is debatable as to whether the project manager role can be undertaken without proper knowledge of ship design, since if certain ship aspects start to unravel, unlike a reduction in the intended combat capability, the whole ship capability is affected. (Thus it was possible for the early Type 23 frigates to go to sea without a full C31 capability while still being fleet units – albeit greatly reduced from the overall and eventual design intent.)

Dr Purshouse also sees naval architects guilty of treating the combat system as a "payload" – I have found it more the case that the combat fraternity (and too often the Defence Staff also) sees the whole warship as made up of "payload" plus "platform", where the former is seen as "good" and the latter "bad" (or at least seeing a "benefit" in the latter's cost being minimised). This is arrant nonsense (and poor systems engineering in not seeing the whole warship as a "system of systems"). For the "platform" component consists of "Float" (clearly essential if the system is at sea), "Move" (a feature of high military worth) and "Infrastructure" (providing accommodation for the crew – largely needed to fight the ship - and the ship's systems, which enable the combat system to function). So a "payload/platform" mind set is wholly false. As a naval constructor who had all the combat and aircraft spaces on the INVINCIBLE Class as his design responsibility, I feel the naval constructor was a much better whole ship aware manager of integrating such spaces into the overall design than specific combat system specialists or process led systems engineers.

So we come to Dr Purshouse's demand for the Chief Systems Engineer to have overall responsibility for the entire solution. – I consider this misses recognising that for a whole warship design:

a) The naval architecture specialist disciplines (such as stability, strength, seakeeping) mean that other peoples' problems (such as weight growth, shock resistance, adequate support services) are directly those of the naval architect as well;
b) The whole ship has significant properties (e.g. stability, strength, whole crew and ship safety, maintaining a mobile environmental enclosure), which are such that if any one fails the whole system fails. Thus the naval architect is not just another sub-system engineer – rather he/she is the System Architect [57].

Dr Purshouse concludes that the electronic system designer's use of "block diagrams" can't deal with physical architecture and "style". – This reflects a major flaw in the S.E. discipline's desire to take over the coordinating role. Better understanding and recognition of the importance of the physicality in Physically Large and Complex (PL&C) systems is vital because.

a) This is where a lot of design problems arise; and
b) Combat sub-systems' impact on the whole system design is largely through the physical elements.

Professor Gates is a combat system engineer with a real knowledge of whole warship design, as his major publications attest. [58]. - His references to key texts and use of the term "Complex Product Systems" matches my use of Physically Large & Complex (PL&C) systems, albeit without the important emphasis on the physically large aspect, which distinguishes ships from other defence systems, not least in the need to provide the man-made environmental enclosure for many personnel for lengthy periods.

Professor Gates asks if the ship concept design provides "sufficient detail for a solution based specification or is appropriate to develop requirements to a more detailed level than Key User Requirements before the exact solution is developed". – This comment again missed the point emphasised in the journal paper. The whole concept phase (concept exploration – concept studies – concept design) is not primarily about producing a design to then be the basis for a further development. It is about "elucidating the requirement" in the dialogue (primarily) with the requirement owner – the defence staff. If this process is successful then the end concept design can provide the basis for the remaining phases of the design to proceed. Thus beyond Feasibility/Assessment, the third phase (Ship Design or Contract Definition) should be the basis for a contract specification, which will contract the shipbuilder to build (fabricate, assemble and test) "the exact solution", namely the physical ship. From the Requirement Elucidation process KURs should properly emerge rather than being imposed from mythical and unrealistic Requirements Engineering.

Professor Gates also mentions "prescriptive solutions". – To undertake requirements elucidation as described in the paper, solutions are produced which are not prescriptive but inform the elucidation with the staff through design options that explore the solution space widely and allow for innovation. If however, the concept phase is part of a competitive process then too often competing bidders will not reveal innovations until the bid process, so these cannot be taken readily into the requirement elucidation process, which ought to be ahead of any competitive process.

Professor Gates considers the Type 45 "ship specification" did not "admit the possibility of innovative approaches". – Such specifications are not about requirement elucidation at concept but the basis for subsequent competing prime contractor's bids see comment on Contract Definition above). Ministries of defence need to decide if completing on inadequately produced Requirements Engineering is good value for money, particularly when concurrent weapon and ship development are separately contracted (as in Type 45 case). **Professor** Gates references the DOORS requirement tools as allowing for innovation. However, if the problem of arriving at the requirements is "wicked" and needs material solutions (1) then such detailed flow down of requirements, which he calls for, must also address whole system (ship) impact, plus affordability and risks. The latter characteristics are only identifiable through interrogating material designs – not abstractions provided by such tools as DOORS.

Mr Macdonald strongly supports the Requirements Elucidation process having observed the opposite occurring with the requirement being "thrown over the wall". – This issue was exemplified by the setting up of the Future Business Group in the UK MoD as the front end of the procurement organisation in the late 1990s. Ironically, I was asked to produce a template for that reorganisation and suggested a "purple" future project group based on the naval directorate for future projects (DFP (N)), where I had been head of concept design in the early 1990s. That team then provided design studies to elucidate requirements with the staff. That this was not subsequently implemented in the FBG, which refused to consider material solutions and adopted non material specific requirements, was severely criticised by Professor John as "bad systems engineering" [4].

Mr Macdonald ends his comments by seeing the engineering of physically large and complex (PL&C) systems as both art and science, making specific reference to Systems Architecture. – SA as being appropriate to PL&C is also the message of Reference 57, with civil architects [59] also considering this approach. With regard to art and science in the design of PL&C systems readers' attention is drawn to a recent publication extensively addressing this issue [60].

Professor Anders Ulfvarson of Chalmers University sees "operations analysis" (OA) as essential systems engineering in a "mission driven design process". – While not disagreeing with the need for OA in such service vessel design, one needs to be careful of being too single mission specific in the design of a naval combatant, whose utility lies in its inherent adaptability. For example the Type 23 Frigate, for which I was concept leader in the late 1970s, provides a salutary lesson. This concept of a towed array frigate to detect and prosecute Soviet SSNs in the GRIUK Gap was designed for silent electric propulsion speeds derived from OA. The first ship came into service in 1989 coinciding with the collapse of the Soviet Union – hence the strategic picture in which the OA was based was instantly redundant. That class of 18 ships has subsequently been used as a fleet escort and even more as "a post-colonial cruiser". So one needs to be beware of being too OA dependant for selecting design choices – in the Type 23 OA guidance saw no justification for a medium calibre gun and one was only eventually added post the Falklands campaign as a sensible piece of pragmatism – not from OA.

Professor Ulfvarson draws attention to my statement at the end of Section 4.1, which is a "judgement rather than his own assessment of the proof". – The question of proof is always difficult with something as multi-functional and complex as a naval combatant and the politically sophisticated process of its design in realsing such a system of systems. How does one "scientifically assess value for money" when at best naval operations can be crudely simulated or in extremis assessed once the fog of a conflict has dispersed?

2. SPECIFIC POINTS

This section covers a series of pertinent points raised by several contributors in shorter comments.

Dr van Griethuysen considers the paper's argument could be improved by showing how the style and configuration actually affects the requirements rather than the solution, in that:-

(a) The configuration demands new requirements;
(b) The configuration encourages the requirement owner to change requirements.

The first of these could occur if, for example, a SWATH solution for a given ship project had improved operability in higher sea states compared to the ubiquitous monohull, but such performance had not been "requested" because it is "known" by the naval staff requirement owner that a conventional monohull could not provide that performance and so they did not specify that (actually desirable) operability in the requirement.

The second could occur if the naval staff did not "ask" for a second large helicopter on a frigate sized ship because they assumed the impact would be excessive (as again would be the case for a monohull). However if a trimaran configuration had have been conceived by the designer as a possible material option then to fit a second Merlin would be incremental. With a proper dialogue with the ship designer this could lead the staff to "have what they really want but didn't think was sensible to ask for".

Dr van Griethuysen asks if the feedback effect (from material studies) would influence user requirements as well as system requirements. – With a requirements elucidation approach the answer must be yes, assuming that the dialogue between design and naval staff had been properly facilitated. This could be seen as an optimistic assumption in current UK procurement practice, especially if contractual barriers exist between concept designer and naval staff.

Professor McKesson points out the naval architects are often too quick to "home in" on "the" ship. – This seems to be a common engineering failure. It stems from not recognising that the Concept phase is quite different from the subsequent phases. It is not primarily about working up the design, which is what most people think is the task of design, rather it is about elucidating the requirements in order to tackle the wicked problem of formulating requirements [1].

Professor McKesson then turns to design tool development and propounds adopting, in concept, "very simple tools". – He is sensible in resisting "the highest possible fidelity", which is not necessary for initial requirements elucidation when primarily the big issues ought to be addressed and not lost in the detailed design downstream. However, sometimes certain issues need to be explored in depth EVEN in concept. For example the RN Auxiliary Oiler concept in the early 1990s was to be the first RN tanker to be double hulled so at concept there needed to be detailed stability studies for every conceivable tank state. This is clearly not something one would do normally until well into Feasibility. So the message is at concept everything is addressed to the minimum level necessary, however that minimum may in certain aspects for a particular design be quite substantial. Furthermore exploration may show some novel design configurations could be attractive and these might need more than simple tools or aspects to be considered, even at concept, in some depth – perhaps requiring substantial simulation studies on a worked up layout [59]. So the further message is that every project is different and strait jackets (like closed black box concept tools or rigid requirements engineering tools) cannot foresee what matters most in the next project.

Professor Brown reinforces the view of Figure 2 that cost and risk implications mean one must do concept designs. – He also mentions the term "Mission Needs Statement" as encapsulating the initial requirement, rather like the "perceived need" as the start point for an overall representation of the ship design process [see Figure 1 in Ref. 58].

Professor Papanikalaou's kind remarks are followed up with the suggestion that the distinction between setting-up requirements for naval and for merchant ship should be more strongly stressed. He also remarks on the power of computers to (quickly) generate thousands of "fairly detailed" solutions to aid the process – Of all the ship design contributors he is distinct in addressing both types of ships. It is interesting that S.E. applied to the maritime domain has largely (but not exclusively) been naval ship design focussed – reflecting the general defence procurement origins of much S.E. practice. With regard to the very large number of "fairly detailed" designs possible to produce at concept and making a wider exploration possible, even in the short bidding phase typical of merchant ship acquisition, it will be interesting to see if merchant ship practice moves towards a more prolonged initial design stage (as in defence acquisition) as owners and the various authorities require greater demonstration of Value for Money.

3. GENERAL SYSTEMS ENGINEERING POINTS

Mr Cooper as a senior design engineer sees the requirements elucidation issue as part of a wider problem with the multi-skilled engineer being side lined and the old chief engineer being replaced by "control management systems". – From my last decade in academia I can see similar problems in research where engineering departments, in the demand for research ratings, have taken on many new academics. These are often more applied physicists than practicing engineers and so better able to get research funds than design engineers. However this has the great danger for engineering education and research of marginalising design in educating future engineers and imperilling the future of UK engineering.

Professor Finkelstein as a computer scientist (and systems engineer) points out that in his field of software management now "weaves together requirements and architecture". He references a paper with this title [49] with a "Twin Peaks" representation showing how the specification "spirals" back and forth from the requirements peak to the architecture peak. – This sounds very like the requirements elucidation dialogue and together with the Systems Architecture initiative, highlighted in Reference 57, suggests naval architects can learn from recent initiatives in complex software design [59].

Mr Skarda, as a former colleague in concept design, emphasises the need to link operational needs with the project drivers of "Performance, Cost and Time". – He reminds us that cost includes through life, aspects which S.E. does have good procedures to address. This is something I have acknowledged previously beyond the critique of Requirement Engineering and to me it reinforces (somewhat against Professor McKesson's comment) the need to use sophisticated architecturally based representations in concept to address such issues.

Professor Wrobel produces seven bullet pointed "do's and don'ts", which in essence call for pragmatism in dealing with Systems .Engineering. – While agreeing the latter, I wonder if S.E. would be better in the Systems Architecture variant [57, 59], as this seems to better address both the concept phase and Design Authority aspect, than does current S.E. practice in the domain of naval procurement.

4. CONCLUSION

All the comments received on the paper seem to support the contention that the approach of Requirements Engineering, adopted for largely political and naïvely commercial reasons in the UK defence procurement practice (and indeed elsewhere) has been quite inappropriate for such complex projects as naval vessels. One might ask why it was thus adopted by a political and executive hierarchy, on the advice of management consultants lacking any domain knowledge for the largest and most complex military projects. This could only be due to the defence hierarchy not genuinely seeking advice of those who had appropriate design experience and had delivered relevant projects on time and in budget. Perhaps if the UK Ministry of Defence had a genuine Chief Engineer on the Defence Council, he or she would ensure the right sort of advice was sought before inappropriate processes were adopted with far reaching implications?

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