MARINE DESIGN

CAN SYSTEMS ENGINEERING COPE?

BY

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ABSTRACT

Systems Engineering is a fashionable and growing discipline, concerning the processes and techniques of transforming a set of engineering requirements into a validated product. It therefore has overlaps and interfaces with both project and design management. It is claimed to be a general panacea for 'coping with complexity'. However many current texts on the subject are strongly dominated by the perspective of information, electronic and aerospace system engineers. For a long time the marine design community has produced some of the largest and most complex products on earth, successfully integrating a variety of technologies over a range of system levels. To do this, it has tended to develop its own language and techniques. However increasingly with the merging of many shipbuilding companies with 'systems' consortia, and the growing importance of information systems, a rationalization of approach is now being demanded.

The article analyses the underlying reasons for the existence of different approaches in different product areas (e.g. marine, aerospace, civil engineering, and information systems). It then explores the usefulness of Systems Engineering as a framework for the management of marine design and production, the degree of commonality with existing approaches, and the extent to which the general guidelines need tailoring to reflect the particular characteristics of different products and industries.

INTRODUCTION

What is Systems Engineering?

Systems engineering is a newly labelled, although by no means a new discipline, concerning the processes and techniques of transforming a set of engineering requirements into a validated product. A growing body of technical literature on the subject has been apparent since the end of World War II.[1] Reference to course notes or textbooks on the subject tend to give definitions such as:

> "Systems Engineering is the integration of those engineering, analysis and management activities necessary for the acquisition and operation of large and complex systems." [2]
>
> "Systems Engineering is about creating effective solutions to problems, and managing the technical complexity of the resulting developments."[3]

or, most simply, from the International Council on Systems Engineering (INCOSE),

> "Systems Engineering is an interdisciplinary approach and means to enable the realisation of successful systems......" [4]

This suggests there could be considerable overlaps with other existing more familiar subject areas, such as design, design management, engineering design, project management and even acquisition management. It is often claimed as a method for 'coping with complexity.'[3] Yet for a long time the marine design community has produced some of the largest and most complex products on earth, successfully integrating a variety of technologies over a range of system levels without the apparent aid of 'systems engineering' — hence the rhetorical question in the title of this article.

A useful starting point for putting some sort of boundary around 'systems engineering' is the graphical representation of the 'V - Diagram' (FIG.1) which is attributed to FORSBERG and MOOZ.[5] This diagram neatly encapsulates the various steps necessary to take a product from a set of high level customer requirements, through the various stages of technical requirement setting and design at system, sub-system and component design and then the matching stages of the integration,testing and acceptance processes. This is very familiar territory, articularly on the left-hand side of the diagram, and is of sufficient generality to be non-controversial.

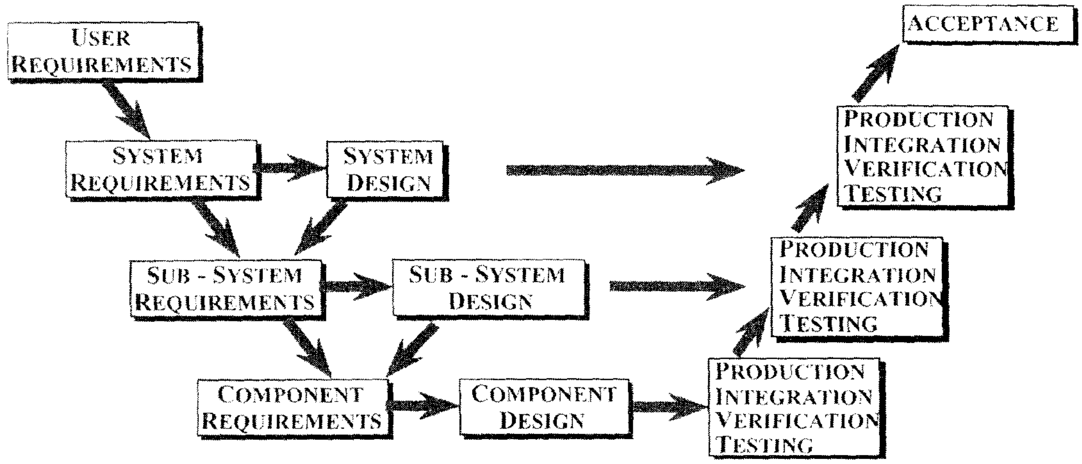

FIG.1 — THE SYSTEMS ENGINEERING V - DIAGRAM

(FIG.2) gives a more recent and wider perspective – the emerging EIA 632 standard from the US Electronic Industries Alliance.[6]

Beyond this process framework, systems engineering concerns itself with the design, analysis and management techniques and tools necessary to conduct the various steps shown in the V-Diagram. This is where a certain amount of 'technical alienation' can occur. Because, recently, 'systems engineering' has been championed most strongly by engineers working in the electronics, software and aerospace industries, texts on the subject, although presented as general, are often highly impregnated with examples and assumptions which are in reality influenced by the nature of those products. One could sometimes be forgiven for getting the impression that the physical design of a space rocket is as trivial as creating the casing for a computer terminal. However, fortuitously, there is one respect in which terminology aligns: in software the highest form of system design is called 'architectural design' – a term with which naval architects are unlikely to disagree!

Another problem for systems engineering is that beyond the common ground of the V-Diagram processes (but not always so elegantly expressed) there is little agreement on the technical and managerial methods to be recommended. For example a review of a random selection of systems engineering textbooks[3,7,8,9] shows little consistent content. It is also notable, but not surprising, that the system engineering techniques, which are championed today, are not the same as those that were highlighted three decades ago. For example in a 1960's textbook[1] emphasis was put on reliability theory, utility theory and network techniques such as PERT, suitable for mechanical or electrical hardware design, whereas more recent texts tend to have a much greater focus on information systems. This is another reminder that what is often presented as general is in fact heavily influenced by the product area, and the 'frontier' technology of the day.

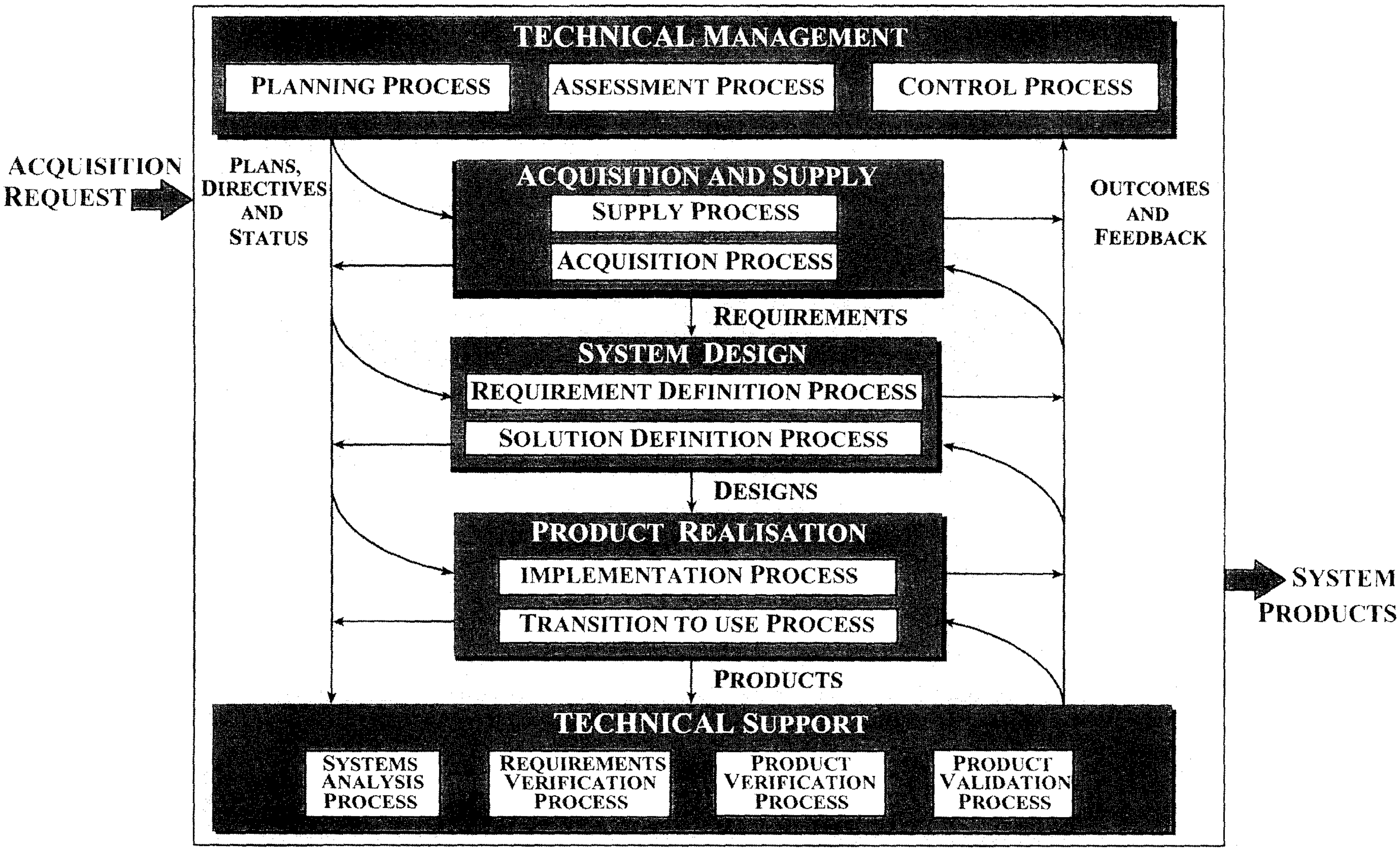

FIG.2 — THE EIA 632 STANDARD

Care has also to be taken to distinguish between 'systems engineering' and other subsidiary subject areas such as 'systems design' and also 'systems analysis'. Whilst systems engineering concerns itself with the overall process (Figures 1 & 2), the latter are effectively techniques within that overall scheme, and generally of a more technical nature. Here again caution must be exercised: the 'system design' method for a physical product will not be the same as that for a piece of software for example. In the latter the main concern is with data flow processes and the intra – relationships of pieces of data. (e.g. using techniques such as data flow, entity – relationship and state transition diagrams[10]). Sometimes what is called (process) 'systems design' in one source[10] is seen, more properly, as part of the 'system requirement process' in another.[3]

The purpose of this article is to explore some of the differences between product areas, in order to illuminate the marine case, and to form a view on the value of systems engineering as a framework for future thinking.

Terminology – Relationship between Project Management, Systems Engineering, Design Management and Engineering Design

An area of potential confusion in the discussion of systems engineering is its scope as a discipline in relation to other activities such as:

- Project management
- Systems management
- Design management
- Engineering design etc.

It is clear that design management activities, as described in textbooks such as reference 11, tend to cover the left-hand side of the V-Diagram in Figure.1. What is arguably additional in systems engineering is the right hand side of Figure.1 – the planning necessary to match the testing and acceptance processes against the flow down of the original requirements. Engineering design texts e.g. references 12, 13 and 14 also have many overlaps with design management and systems engineering but naturally tend to emphasise the creative challenges and techniques of the design synthesis task at the concept stage, rather than the more bounded downstream development and acceptance activities. They also rightly tend to bring out the very iterative nature of the very early requirements setting and system design.

Differentiation with project management is more problematic (see for example the original definitions given on page 233). Again there are significant overlaps, and many of the techniques of systems engineering are also claimed in project management literature. ARNOLD, BROOK et al[3] make the convincing distinction that systems engineering provides the creative heart of project management by defining the technical and work deliverables i.e. the requirements, the design and all the tasks necessary to build, integrate and test the product. Under this view project management then becomes the activities associated with implementing and controlling the 'product and process blueprint' which systems engineering has provided. Thus, contract management, scheduling techniques, cost control, configuration management, QA etc. are activities which have no meaning without the foundation of systems engineering (FIG.3). An alternative, but related, view is not to see project management and systems engineering as separate disciplines, but is to see project management simply as the larger canvas which must include systems engineering, just as systems engineering must include design. This properly implies that systems engineering activities must be project managed just as much as full-scale product development needs to be.

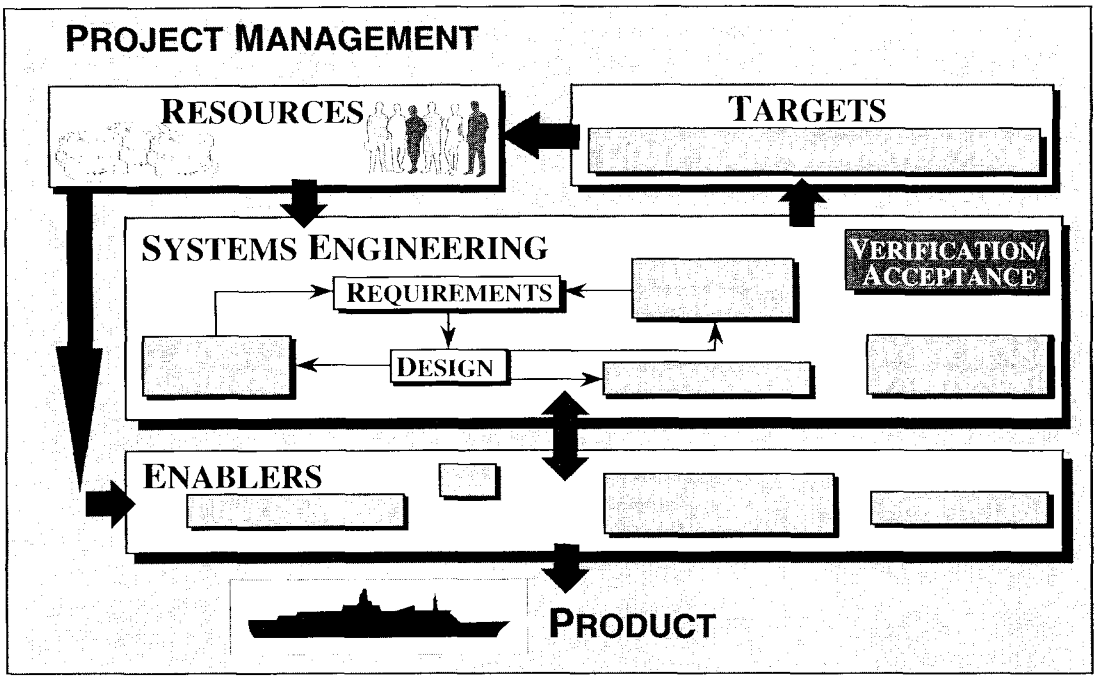

FIG.3 – RELATIONSHIP OF PROJECT MANAGEMENT AND SYSTEMS ENGINEERING

INFLUENCE OF PRODUCT CHARACTERISTICS ON ACQUISITION LIFE CYCLE PROCESSES

It is interesting to consider some of the ways in which the nature and characteristics of different products influence the approach to acquisition, from initial requirement setting through systems engineering processes to in-service support.*

High Performance/Technical Complexity (e.g. Aircraft, Missile System)

A high performance/technically complex product such as an advanced aircraft or new missile system is likely to be distinguished by the fact that the requirements go beyond existing capability in some way. The immediate consequence is that the product will require development involving considerable expenditure and time, as well as a specialist expertise in design and manufacture. Because of the performance risks, design and production will need to be given to the same contractor (i.e. a 'Design and Build' philosophy). Development will require a number of prototypes and integration facilities, with production carried out in a manufacturing environment. Because of the high degree of expertise in design and manufacturing it is likely that the development contractor will also carry out in-service support.

Software Intensive Product (e.g. C^3 System)

Software Intensive products will typically have requirements, which are demanding both technically (e.g. speed of response and data volume) and by the number and complexity of the functional requirements. Non-consumer item products are often large, and developed from bespoke requirements, which are likely to evolve. Additionally many of the functional requirements will need an interface with human operators, so there will be a large degree of customer/user

* The following observations are of necessity generalizations, for which there are no doubt exceptions

involvement in the design testing and acceptance process (e.g. PRINCE* methodology of the UK Government's Central Computer and Telecommunications Agency[15]). Indeed many of the true requirements may not emerge until this phase. Although the actual production of software is trivial, configuration management is not. Software dominated systems may also be safety critical which, because of the complete nature of any failure (ARIANE V!), will require considerable care in planning the testing and validating process. In-service support will be carried out by the development contractor.

Lived-in environment (e.g. Building)

A product, which is lived-in, as opposed to, simply operated, will demand particular characteristics. The requirements are usually 'one-off' and bespoke. Architectural requirements such as aesthetic beauty, layout and habitability are very difficult to define precisely in words. Instead broad target requirements are likely to be set and the selection of the final arrangement made from a number of competitive sketch designs. This architectural layout solution then enhances the original requirement and forms the basis on which the detailed building design can then be organized. For built civil engineering products it has been common that project management/design and construction are carried out by separate design/engineering consultants and contractors.[16] Increasingly, however, the benefits of 'design and build, and (sometimes) operate' type contracts are now being recognized for projects where the technical risk is significant.

Passenger carrying function

The carriage of passengers will require particular attention to human factors, and requirements such as safety, quality and comfort. Aesthetics and 'brand image' will also play a large part in the design of the product, requiring early attention to these aspects and approval by the operator.[17] The design of such products with respect to safety will be closely controlled by Government regulations – either national or international. This will be particularly acute for products that carry a large number of passengers where the loss of life from a single incident would be high.

Operation in harsh/hostile environment

For products which operate in a harsh or hostile physical environment, the demonstration of safety, reliability and other 'non-functional' requirements may assume a large importance compared to products dominated by functional requirements e.g. software. These aspects will also attract the attention of regulatory bodies – doubly so in the case of lived-in environments or passenger carrying vehicles – and need suitable demonstration of compliance of the product design and its operation.

Physical size

The physical size of a product will influence the location and manner of construction. Large products such as buildings and ships are assembled rather than manufactured, and need to be built on site because of the difficulty of transport. Of course modules and sub-units may be transported to the final assembly site. Smaller products can be produced anywhere and transported to customers.

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* **PR**ojects **IN** **C**ontrolled **E**nvironments

Unit cost and numbers produced

The unit cost of a product, both in absolute terms and relative to the total production cost, will have a strong influence on whether it is affordable to use prototypes in the development process. Technical risk will also influence the choice. Thus in the case of aircraft, where relative unit cost is small, but performance risk is significant, it is normal to use prototypes, whereas this is not normally the case for whole marine vehicles. The quantity of the product produced will also influence the production and acceptance regime adopted. If the production run is high, it is worthwhile standardizing the manufacturing method (possibly with automation) to a closely defined QA build standard. The converse is true where the production run is very small. In this case full acceptance will be required for each unit. Again aircraft and ships illustrate these two extremes. Large production runs also encourage the use of batching as a means of striking a compromise between configuration stability and change management.

Length of construction

Large complex products will take a long time to build. They are also likely to be expensive and not produced in large numbers. This means that the pressure to introduce change during construction will be greater. The length of time also increases the chance of major changes in the political, social or economic environment. (See reference 16 for discussion of CONCORDE and nuclear power).

Length of Service Life

The length of the service life will influence the manner in which the product is supported through life. For relatively simple technologies e.g. buildings, any number of contractors will have the expertise to carry out maintenance. This is fortunate for these products will also last for many decades if not centuries (e.g. bridges, major public buildings). Alternatively if the product is technically demanding in its design and manufacture it will initially need to be supported by the development manufacturer (the 'Design Authority'). A long service life may lead to problems in continuity of support if the contractor or his expertise disappears (voluntary or involuntary).

CHARACTERISTICS OF MARINE VEHICLES

Product characteristics

An attempt to relate the product characteristics outlined above to product types is shown in Table I. It can be seen that marine vehicles are relatively unique in the extent to which they 'score' against nearly all the characteristics previously considered. Although marine vehicles do not generally require a large amount of development as assembled products, this is not necessarily true at sub-system level where major development, often with considerable software content, may be required. It is this complexity, range of system levels and technologies which makes ships a 'system of systems' and can constitutes a considerable dilemma for the optimization of the overall acquisition philosophy and the tailoring of systems engineering methods.

TABLE I – *Characteristics of Product Types*

PRODUCT CHARACTERISTIC	Bespoke Requirement	High Performance	Software Intensive	Lived-in Environment	High Unit Cost	Large Size	Long Service Life
PRODUCT TYPE							
New Office Complex	X			XX	X	X	XX
Advanced Missile System	X	XX	X				X
Command System	XX		XX				X
Commercial Ship	X	x (sub-system)		X		XX	X
Warship	X	xx (sub-system)	xx (sub-system)	X	XX	X	X

XX – Denotes that product characteristic apply strongly.
X – Denotes that product characteristic applies.

Design process characteristics

Another influence on systems engineering is the nature of the design process resulting from the mix of systems and the different integration needs. The key components of the marine vehicle design process, which must be brought together, are shown diagrammatically in (FIG.4):

(*a*) *The physical design and integration of the marine vehicle.*

The layout or architectural design together with the assurance of the mechanics of the vehicle (weight and space, stability, powering, structural strength.) and the definition of the product breakdown of the overall design.

(*b*) *The design of systems dealing with the handling of data and information.*

e.g. for a warship with a wide variety of different equipment and human interactions, which must be co-ordinated to work as a whole under extreme response time pressures and complexity, this is a major challenge.

(*c*) *The 'human factor.'*

A ship is also a lived in environment that must be manned. This obviously interacts with both the physical design of the ship and the need to interface with information systems and the ability to make correct and timely decisions.

(d) *The design of sub-systems (includes the development or selection of their equipment).*

This of course interacts with the other 3 aspects. For example there is a trade-off between equipment automation and reliability with the number of people to man or support it in service. There is also a need to decide between hardware, software and human partition of tasks. The level of effort and risk will depend on the balance between 'development' and 'non-development' items. Good sub-system specifications, and interface control, will be the key to a successful procurement and integration of these sub-systems into the overall system.

Although all of the above aspects need to be addressed in marine vehicle design the relative dominance of one 'domain' relative to the other will of course depend on the type of vehicle and the particular requirements of a given project. In the past the physical design (i.e. left hand side of Figure 4) has dominated the thinking of naval architects and marine engineers. However increasingly the management of information has become important, particularly in warship design.

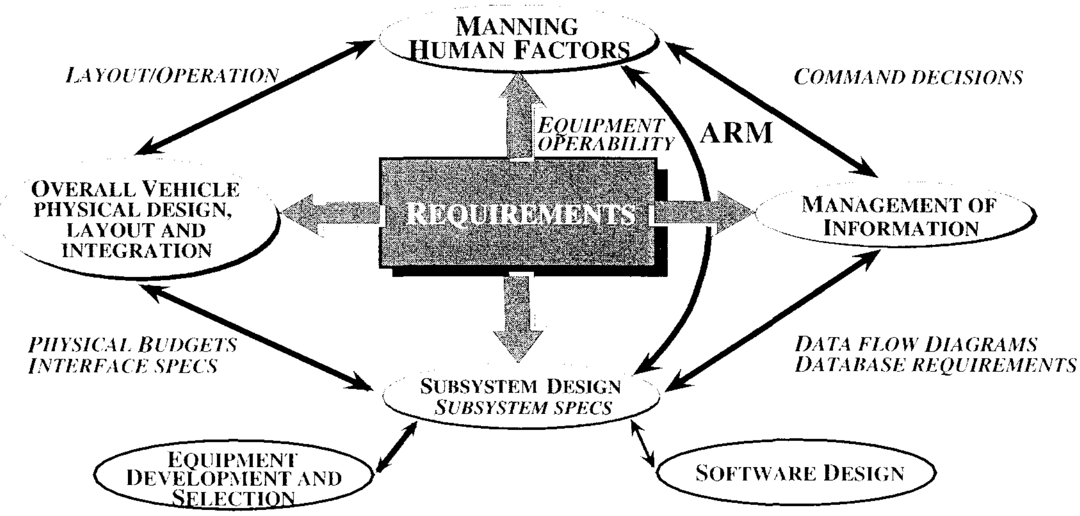

FIG.4 – KEY COMPONENTS OF MARINE VEHICLE DESIGN

MAKING SYSTEMS ENGINEERING WORK FOR MARINE VEHICLES?

Any rational approach to systems engineering and acquisition must match and tailor the general principles and methods used to the characteristics of the product and project.[2,3]

The purpose in this section is therefore to build on the previous analysis to consider the approaches, which might be appropriate to the marine vehicle case, and to explore some of the more difficult issues that can arise.

Nature of System Requirements and Systems Design

As in the design of other mobile vehicles such as aircraft, for marine vehicles there is a very strong interaction between the system and sub-system design levels through mechanisms such as weight and size (FIG.5). This interaction is much weaker for static structures such as buildings and is trivial for software systems. This puts a premium on good synthesis models of the overall design and indicates the importance of good design modelling before finalizing sub-system requirements. It also indicates the importance of good estimation in allocating budgets to those responsible for developing the sub-systems. This is an excellent example of where so called 'design synthesis tools' are absolutely essential for the successful implementation of some systems engineering processes in specific engineering domains. It is in truth difficult to see where systems engineering ends and design starts.

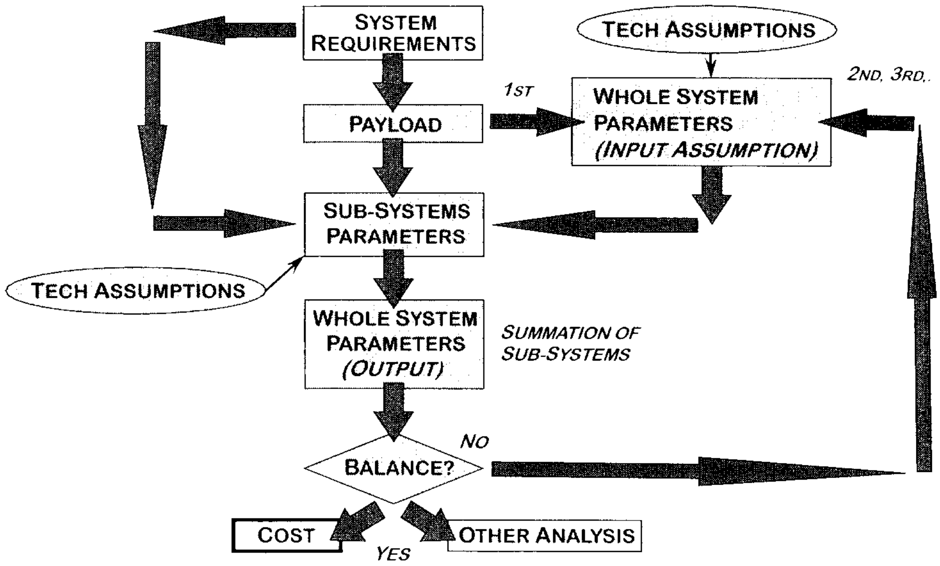

FIG.5 – GENERAL SYNTHESIS MODEL FOR MARINE VEHICLE

Sub-System development items

The general system engineering life cycle model (Figure 1) makes the inherent assumption that system design precedes the generation of sub-system requirements and then sub-system design. This is often not the case for marine vehicles if the system level design requires relatively little development while the sub-systems require substantial development. In such cases the latter will dictate the overall cycle time and become a constraint on the system design. (FIG.6) presents a number of potential problems if the development activity has to start many years in advance. First the sub-system design may be carried out in isolation of a particular vehicle. Secondly it is likely to mean giving an initial development contract to a contractor other than the eventual prime-contractor, raising later issues of responsibility for both system and sub-system performance. This is often seen in warship procurement. The solution to this problem lies in the procurement organization taking an early upstream systems engineering approach across all its future projects.

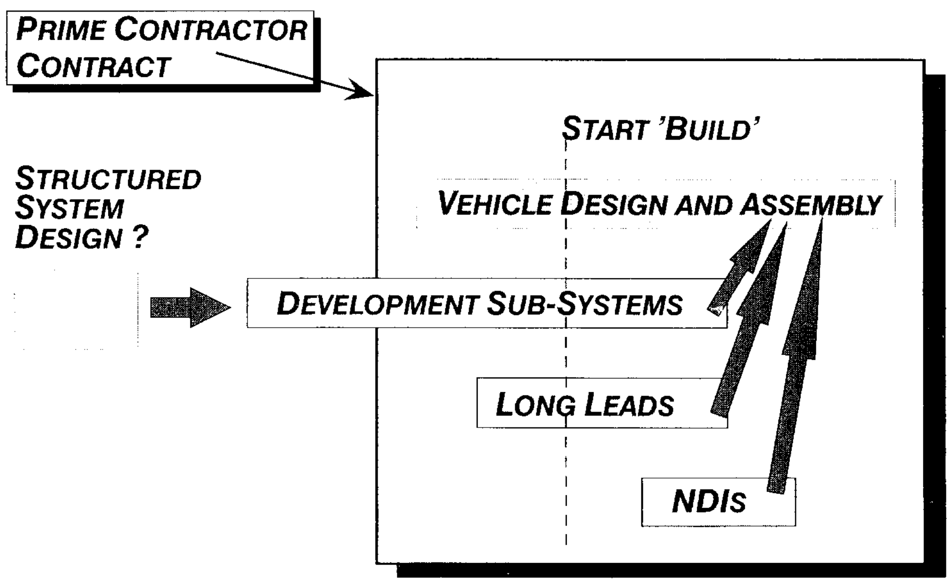

FIG.6 – MARINE VEHICLE PROCUREMENT PROCESS

System and sub-system life – Incremental physical acquisition

A significant systems engineering issue for marine vehicles is the potentially different operationally useful lives of the overall marine vehicle (say 30-40 years) compared to some of its sub-systems, particularly those which use a large amount of software or are in other ways performance critical. In the initial design this requires careful attention to margins for both the physical parameters (weight, volume and power supplies) and possibly for data storage and handling, although improvements in technology have tended to 'overrun' such calculations.

Testing and acceptance

Marine vehicles demand particular care in the testing and acceptance process because their high unit cost and small numbers generally precludes the luxury of a prototype of the overall vehicle. Instead a strategy of prototyping high-risk sub-systems will need to be adopted, along with shore test facilities for carrying out development and qualification testing of complex sub-systems prior to installation on board.

Another important caveat for marine vehicles is that because mistakes discovered late are mistakes which are difficult to resolve on units destined for ultimate operational service, the philosophy of progressive testing and auditing through all the 'layers of the onion' is essential. It is also important to recognize that certain aspects of the overall design, which cannot be tested until the final system level trials, and could not be easily changed (e.g. defective stability because of ship dimensions or an inadequate layout) are reviewed at intermediate points. This concept of 'plan approval' is standard practice in the commercial marine world but goes against the grain for some that have worked in other product sectors which can rely on prototype testing.

CONCLUDING REMARKS

We have seen that in many ways systems engineering is no more than a generalized model of – and a framework for thinking about – the engineering process, which needs tailoring to be applicable to a particular product and project. It is therefore self evident that marine products have always been designed and produced using a form of 'systems engineering' even if those particular words were rarely used. It is also true that much of naval architecture and marine engineering concerned with design management is undoubtedly an example of systems engineering. Thus to answer the rhetorical question set in the title of the article, it is not so much a question of whether 'Systems Engineering can cope with Marine Design,' for in principle it undoubtedly can, but more a question of whether in its current 'born-again' form – as represented by the recent body of literature and course specifications with those words in their titles – it has anything to offer beyond our existing understanding of the management of engineering. The positive aspects of the new interest in systems engineering are considered to be:

- Although to some extent a fashionable 'bandwagon,' it has – as bandwagons go – the very great merit of putting the focus on engineering as the creative heart of the management of projects, replacing the somewhat sterile process of monitoring implementation of magically produced solutions with project management tools.
- The promotion of systems engineering should encourage 'joined-up' engineering, although this also needs to be followed up by the development of a greater variety of practical tools suitable for real

situations, products and technologies. Otherwise it will remain an aspirational discipline with little real value.

- Although existing systems engineering texts – often with a bias towards software/computer systems – appear not to offer anything new for the overall system design process of physical marine vehicles, there are techniques and insights to be learnt in the area of requirements rich process/information systems. As marine products become more influenced by software systems these methods need to be added to the marine design management 'toolkit'.
- Systems engineering encourages careful planning of the testing and integration process, including the need to trace requirements through the design process to acceptance which goes beyond the traditional (lack of) emphasis in the teaching of 'design management'.

However, a few words of caution are offered in the following areas:

- The current language of systems engineering has to some extent been 'hijacked' by engineering communities working in particular product sectors. What is presented as 'general' is in fact often, and unwittingly, 'partial'. This is especially noticeable in chapters dealing with 'systems design' which can be heavily software based, and can lead to a sense of alienation for many engineers involved in the 'engineering of systems' when faced with 'systems engineering' texts. It would undoubtedly be helpful to its wider acceptance, if systems engineering publications and courses used more significant examples from a wider product base, and gave due prominence to the physical aspects of the design of complex products. This is now being done on some new courses e.g. reference 2.
- Product differences should be researched more, particularly in the area of system design. Armed with this awareness, engineers could then approach each task in a spirit of rationality and select the most effective methods.

Systems engineering is no magic panacea, and can do positive harm if procedures are applied across products in an inappropriate or disproportionate manner. For example the over elaboration of requirements in computer databases, under the banner of 'requirements engineering', without progressive design modelling to establish feasibility in terms of cost and in-service date.

Whilst the concept of systems engineering, as an area of knowledge, methods and techniques which can be applied to different product areas is a valuable one, the further step of defining systems engineering as a separate professional branch is highly debatable – to say the least. To do so would imply that there is such a thing as a generalist system engineer who can carry out his work in isolation of any real product/industry domain knowledge. It is surely a much more positive approach to concentrate on giving all engineers an understanding of systems engineering principles and to support this with appropriate cross disciplinary awareness and the proper work structures to encourage good design.

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