

# Systems Engineering – a road from perdition

David Stupples<sup>1</sup>

**Abstract:** Today's complex engineering systems are substantially multi-disciplinary but universities are still producing engineers that are essentially skilled in a single discipline. In world economic terms, if the UK is to maintain its position as a leading technological nation then it must move higher in the engineering food chain and become a leading systems integrator. To achieve this position, academic engineering education in the UK must change to incorporate systems engineering. The Royal Academy of Engineering is best placed to bring about this change through its contacts with government. Using a three level model for systems engineering proposed in this paper, the RAEng together with the engineering institutions and INCOSE should persuade government that systems engineering is key to the economy, and encourage universities to incorporate necessary syllabus changes, with a different focus for universities that wish to concentrate purely on engineering and others wishing to combine engineering with systems engineering.

## Introduction

Today's complex engineering system solutions are substantially multi-disciplinary in nature and encompass variety in functionality resulting in levels of complexity that grow exponentially year on year (Blanchard and Fabrycky, 1998). National Audit Office (NAO) reports (2004) suggest that the UK is now trailing other major economies in its ability to realise complex engineering systems (especially in major infrastructure), and this is further evidenced by the growing trend to import systems engineers from the US and mainland Europe to lead integrated systems design activity.

The government has recognised that the UK needs to be a competent systems integrator if it is to remain in the technology premier division. Furthermore, the Royal Academy of Engineering (RAEng), following a study by four of its fellows (McDermid et al, 2003), introduced a new 'visiting professor' (VP) scheme to help selected universities augment or modify their undergraduate programmes to incorporate education for 'integrated systems design'. For the purposes of this paper, the accepted discipline of 'systems engineering' will be used to cover all aspects associated with engineering at the systems level in order to maintain consistency of view, and as an encompassing discipline for integrated systems design.

Most universities have failed to address the academic training required for engineers to design, build and operate large and complex engineering systems. Instead there is a belief, especially by some of the more influential universities, that growing single discipline engineers within industry will suffice, or worse that single discipline engineers already have all the knowledge needed to handle complex systems. Knowledge of systems engineering within universities is varied with a significant number just viewing the subject from a single engineering mindset. Others would accept cross-discipline aspects within a limited technical framework, but few comprehend the links to business, economics, social engineering, and finance. A review of US universities provides a contrast, with a large number offering electives in systems engineering and integrated systems design. MIT for instance, focuses its systems related courses through its Department of Engineering Systems which is considered a

---

<sup>1</sup> Dr David Stupples is a RAEng VP for Integrated Systems Design at City University, London, where he is also Professor of Systems Engineering. Formerly, he was a senior partner with PA Consulting where he was international head of systems engineering.

world leader. It is perhaps an indicator as to why US industry leads the world in large-scale systems implementation.

Incorporating systems engineering into existing university engineering courses in the UK is difficult for a three reasons. Firstly, some existing courses are aimed at producing research and development engineers for a single engineering discipline and accordingly have received accreditation from an associated or sponsoring engineering institution, and adding further subjects could not easily be accommodated within an already crowded syllabus. Secondly, some courses address engineering system applications within a single discipline, and universities offering these courses believe that they already teach systems engineering. Thirdly, there is a shortage of competent and experienced systems engineers in the UK making it hard for universities to recruit and retain appropriate academic staff. Through the RAEng Integrated Systems Design (ISD) VP scheme it may be possible to progressively introduce systems engineering (SE) at an academic level, but it will need careful planning and a high degree of persuasion.

This paper provides an overview to the scope of SE in order to identify its academic foundation. It then defines three levels of system for application of SE; systems within a single engineering discipline, systems that span two or more engineering disciplines, and finally systems that span two or more engineering disciplines but also incorporate significant interfaces to a wider systems environment comprising social, political, economic and business systems. The latter class of systems generally includes major infrastructure, but none of the three levels should be considered as distinct as significant overlaps occur between the levels. Finally, the paper reviews the US and UK position on SE education performance, draws conclusions and makes appropriate recommendations.

## **Systems Engineering – what is it?**

This section provides an overview to systems engineering by providing a historic précis, a thumbnail sketch of the processes involved, and a brief look at the science and education involved.

### ***Historic Précis***

With its roots in the Bell Telephone Laboratories in the early-1940s, systems engineering (SE) was developed as a hybrid engineering/management methodology to realise a rapidly expanding and increasingly complex telecommunications infrastructure in the US. In its original form SE had a distinct operations research (OR) flavour within its problem definition and synthesis activities that were modified to deal with very large systems, and this was further enhanced by methods and tools from the emerging new discipline of systems science and Cybernetics (see Wiener 1948, Bertalanffy 1950, and Ashby 1966). Early SE had the potential to become a sound technical/managerial discipline for realising complex systems as it employed a formal and rigorous analysis foundation. It was further developed for space and missile programmes in the 1960s and 1970s but was evolving towards a process focused technical discipline linked to project and programme management and was losing its analysis foundation.

In 1974, the newly developed Mil Std 499A stated ‘that SE was the application of scientific and engineering efforts to: (1) transform an operational need into a description of system performance parameters and a system configuration through the use of an interactive process of definition, synthesis, analysis, design, test, and evaluation; (2) integrate related technical parameters and ensure compatibility of all related functional and programme interfaces in a manner that optimises the total system definition and design; (3) integrate reliability, maintainability, safety, survivability, human and other such factors into the total technical engineering effort to meet cost, schedule, and technical performance objectives. It was silent on the detail concerning methods and models for systems analysis and reflected the then current US Department of Defense (DoD) Equipment Acquisition Process.

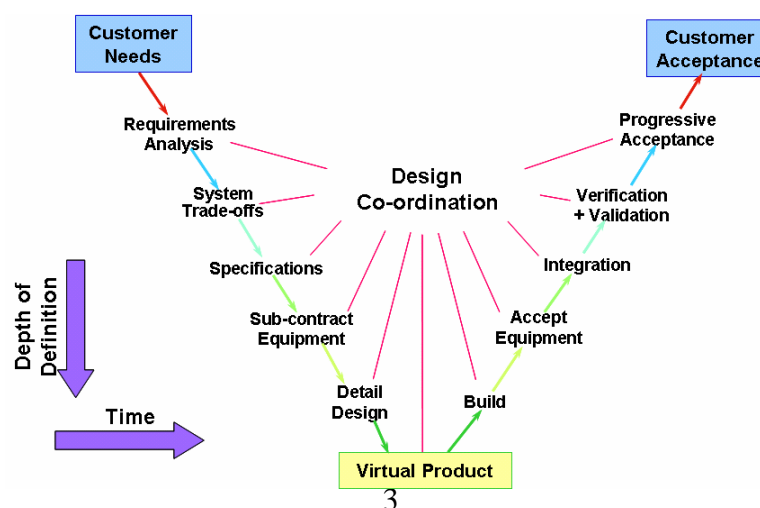
This standard together with its successor Mil Std 499B (1994, draft only), although technically comprehensive in process terms, betrays the original scope and value of SE by omitting its theoretical base and avoiding consideration of the Wider System of Interest (WSOI - the system that contains the system under development or modification); an omission that has been material in many failed complex systems implementations (Stupples, 1995). This betrayal was due in large part to a focus on military applications with many engineering companies in the US working exclusively on military projects with their process driven cultures. Checkland (1975) recognised that the WSOI with its interfaces from socio-economic, political and business systems to the technical system in question were messy and could not be handled using traditional SE methods and tools and hence the Soft Systems Methodology (SSM) began its life. Checkland divorced himself from mainstream SE with the result that methodologies begun to diverge. Other 'soft system' methods grouped under the term 'systems thinking' followed the 'soft' path. Most of these methods are process driven and have been developed to assist decision making in complex situations. This has led to the current state where SE is being practiced for the large part as an engineering process, and systems thinking as a management process. Jackson (2005) provides good insight into this divergence and recognises that reconciliation is necessary.

Jay Forrester in 1961 at MIT also recognised the need to take a wider systems view if complex engineered systems were to be realised successfully and developed system dynamics which could model both the WSOI and the system being developed in harmony but at a level where much of the detail is consolidated. The first real attempt at defining an SE methodology to deal with large-scale complex engineering systems, ie where systems are embedded into their softer environment was provided by Hitchins (1992). He advocated a total systems engineering approach going some way to harmonise systems theory, systems engineering, and systems thinking. From the early Hitchins' work and that of the research by M'Pherson and Stupples (all three from the City University Department of Systems Science) grew a more all embracing SE approach.

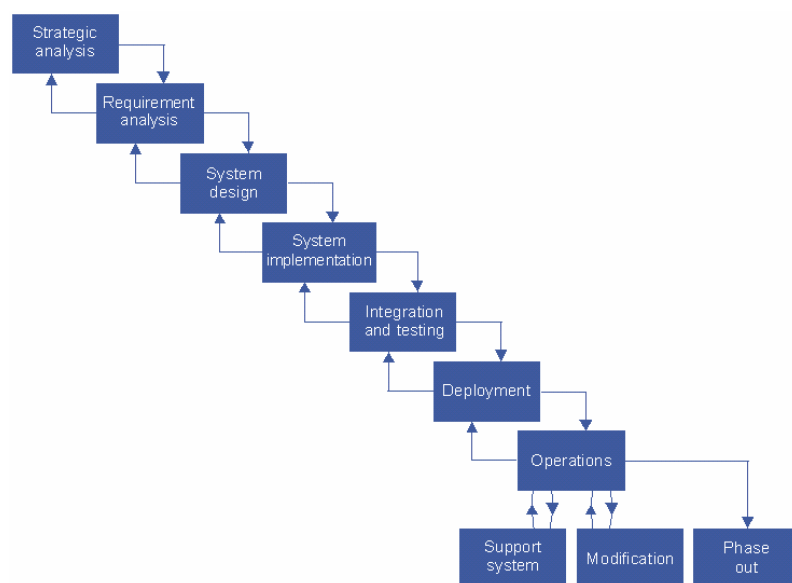
The now accepted definition of SE is given by ISO 15288 together with its underpinning methodology and body of knowledge developed by the International Council on Systems Engineering (INCOSE). However, SE has sadly lost its science foundation and is being practiced widely as the application of management processes to systems design and hence information required for decision making under uncertainty is not being generated. The requirement for this science foundation is stated clearly within the SE competences detailed by INCOSE and therefore the recognition has not been lost but the science has.

### *The SE process*

The quintessential 'V' diagram provides the icon for the SE process map. This icon unfortunately gives the impression that SE merely gathers traditional engineering techniques under one banner with no value added. The 'V' diagram, one example shown below, provides a route map for the ordered application of systems design processes, and shows the systems engineer in the key coordinating role.



The systems lifecycle waterfall diagram provides a more comprehensive view of the scope of SE as it shows the whole lifecycle of a system from cradle to grave as shown below (a simple model for illustrative purposes). It is clear from this diagram that a major interest of the systems engineer occurs after the system is delivered; it must perform to meet the acceptance test criteria, but cost of ownership, upgradeability, business performance, social impact, public safety, reliability, and political fallout will take on a higher profile than the implementation phase. The Channel Tunnel is an example where the later lifecycle performance is now suffering from poor systems engineering at the outset. A report from the Major Projects Association (MPA) (2001) identified the need for whole lifecycle design, and an external study for the MoD led to the introduction of the Smart Procurement Initiative to ensure the future military equipment was affordable.



However, the NAO frequently comments on cost and schedule growth caused by systems integration and design issues (eg, NAO 2000). The operational elements of the armed forces and business leaders complain that cost of ownership of engineering systems is too high and that poor integrated systems design is often to blame. Furthermore, business leaders together with government ministers are fearful that unless the UK develops its capability in design and integration of large-scale systems it will lose much of its technological leadership. A closer investigation of the work undertaken within each process reveals, in many cases, missing systems analysis and modelling which has led to a non-optimised design.

### ***The science that underpins systems engineering***

The current situation reflects the migration route of systems engineers from single engineering disciplines with little or no knowledge of either systems science or systems analysis. But modern complex engineered systems are now all pervasive and require to be engineered as total systems. To undertake integrated systems design for these total systems a different breed of engineer is required that has a broad range of engineering skills and the ability to undertake analysis on a systems-wide basis by understanding system's performance and behaviour. The knowledge required for engineers responsible for the realisation of pervasive total systems includes:

- A broad engineering knowledge covering the whole engineering spectrum similar to engineering sciences courses offered by a number of universities in the UK.
- Knowledge of systems science covering systems theory, systems modelling and systems mathematics.
- Knowledge of decision science covering operations research, systems analysis, and probability.
- Knowledge of systems economics and social theory that impacts the wider system within which an engineered system may reside.
- Knowledge of cognitive and behavioural psychology in order to deal with the human aspects of systems; this is particularly relevant where systems safety is to be considered.
- Programme, project and operations management involved throughout the system's lifecycle.

Rhodes and Hastings (2004) identified four constituent skill elements for SE; systems architecture and engineering, operations research and systems analysis, engineering management, and technology and policy. Rhodes and Hastings claim that the need for this skills mix has emerged through consultation between MIT and its industrial partners.

Systems analysis (SA) was developed by the Rand Corporation for the US Air Force to apply mathematical modelling to complex military problems. The Rand Corporation evolved to be an independent 'not for profit' organisation applying SA techniques (see Miser and Quade) to world problems with considerable success. The SA techniques are now widely used by the major management and technical consultancies to address difficult problems in the socio-economic, socio-technical and political arenas. The results from the application of SA often underpins public policy decisions.

## **The Levels of Knowledge for effective Systems Engineering**

SE is still an evolving discipline and is suffering from an unfortunate lack of a universally accepted definition and understanding, and this is reflected in the education of engineers offered by universities. To accommodate existing university education and the needs of the commercial world, it is necessary to define system engineering on a number of easily recognised levels. Definition of these levels together with the required knowledge for each level is addressed in this section.

### ***Levels of System Engineering***

Not all engineers working in systems design and implementation would need the full scope of SE education as many systems can be viewed as 'substantially contained' within a single engineering discipline and therefore some pragmatism and flexibility is required if SE is to be adopted academically. A three-level structure is offered as an approach to addressing the problem:

- Level 1 – systems substantially within a single engineering discipline. Such systems could include embedded systems, computer systems at a hardware level, automobile transmission systems, in-vehicle electric power generation, data transmission systems, and cryptographic systems. Most engineering schools and departments could claim that they teach systems engineering at this level.
- Level 2 – systems substantially covered by two or more engineering disciplines. Such systems could include telecommunications systems, aircraft systems, computer systems, power generation, engine management systems, manufacturing systems, railway signalling and control systems, and traffic control systems. Some systems at this level could be classed as 'systems of systems' or 'network of systems'. Many of the focused SE courses in the UK and elsewhere claim to provide education at this

level although most avoid teaching systems science and advanced analysis techniques. Furthermore, many of the focused SE courses have been sponsored by defence industry business and they reflect a distinct flavour that often will limit the scope of courses particularly in architectural option analysis.

- Level 3 – systems that cover two or more engineering disciplines and that have substantial impact on wider system aspects including economic, societal, environmental, and political. Most of the systems at this level could be classed as ‘systems of systems’ or ‘network of systems’ and include national power generation and distribution, road, rail and air transport, gas supply and distribution, air traffic control, military command and control, and enterprise-wide solutions.

It should be noted that the level categorisation does not imply a difficulty or complexity hierarchy as a system within level 1 could be conceivably more complex than a system at level 3. The hierarchy is a convenient partitioning for identifying education requirements. Hitchins (1992) offered a five-level model citing product system, capability, business, enterprise and socio-technical. The three-level model essentially integrates Hitchins top three levels in order to offer a simple education model that is easier to implement within the current engineering education establishment.

It is normal practice for systems engineers to assume that parameters related to the wider system, ie the containing system, be considered as constraints. This approach is widely used in the implementation of systems within levels 1 and 2 and can be traced to defence and aerospace industries where systems are developed to a fixed budget with constrained time schedules. Moreover, many of the level 1 and 2 systems are in reality subsystems and therefore interfacing constraints introduce a restriction on design flexibility. On the other hand, systems within level 3 serve society or an enterprise and the interdependencies are treated as variables and not constraints, and therefore a wider knowledge is needed to deal with them. Moreover, it is unlikely for a network of systems at level 3 to be developed from a ‘green-field’ state as such systems are usually being constantly evolved through upgrades while maintaining full operation; eg, the national rail network.

### ***Levels of Knowledge Required***

The levels of knowledge required for each systems level are identified below:

- Level 1 – engineering discipline knowledge, systems engineering\* and architecting, modelling and simulation.
- Level 2 – engineering science (cross discipline perspective), single engineering discipline knowledge (for the dominant discipline), systems engineering\* and architecting, modelling and simulation, operations research and systems analysis, technology policy, and management.
- Level 3 – engineering science, systems engineering\* and architecting, systems science, modelling and simulation, operations research and systems analysis, economics and social policy, technology policy, government policy making and decision taking, and management. This level will require system engineers to have a good knowledge of how the WSOI, which in most cases will be a societal network of systems or its military operations equivalent, will interact and behave with the system being realised. To achieve this level of knowledge engineers will require a much broader education than has hitherto been provided.

\* General systems engineering education should include the processes and analysis necessary for systems lifecycle design and management as defined by Blanchard (1998), and this education should apply to all of the identified levels. The education should also comply with the SE core competences defined by INCOSE in order to achieve academic and commercial consistency.

The levels of knowledge described are reflected by Adcock (2004) who identifies the need for formal SE principles and a detailed knowledge of advanced analysis techniques to underpin SE education if it is to add value. Adcock also identified SA and systems thinking as necessary prerequisites, but did not address the need for systems science to address complexity.

## **Educating Tomorrow's Systems Engineers**

Accepting that the US is currently the global leader in the education and utilisation of system engineers it makes sense to provide a comparison of SE in the US and UK

### ***SE Education in the US***

According to a study by Fabrycky (2003) there are 94 postgraduate courses in the US covering systems engineering. A more detailed analysis of these courses reveals that 60 relate to SE levels 1 and 2 with some coverage of level 3. Thirty cover significant elements of level 3 with for around four covering nearly the entire requirement for level 3. Of these MIT, Pennsylvania University, and Stevens Institute appear to be leading the field. Undergraduate study in the US tends to be more engineering science related with specialisations being achieved through post graduate study. Fabrycky identifies some 20 colleges and universities offering undergraduate degrees in systems engineering, but these relate in general to levels 1 and 2 described in this paper. Furthermore, for undergraduate courses in general there is a large number of electives available (many thousands) that relate to aspects of systems engineering – particularly associated with decision sciences. From initial estimates around 10,000 students each year select elective courses that would assist with the engineering of systems.

A large number of company in-house schemes exist particularly in companies involved in defence contracts where SE is considered as part of the requirement. Of the schemes reviewed for this paper, all focus on the process used by particular companies with reference to related government standards – eg, the SE processes required under the DoD Equipment Acquisition Programme, or under the NASA Systems Engineering Standards. The schemes appear to assume that knowledge of required analysis methods already exists or will be provided through post-graduate study. Many US companies require SE post-graduate study to be a prerequisite to advancement – reflecting the importance attached to SE.

It is estimated that the US produces around 300 systems engineers each year capable of undertaking level 3 work.

### ***SE in the UK***

The UK on the other hand is less well served, even considering the size difference in economies. Many UK universities purport to educate systems engineers as their courses contain the word system or address minor system's aspects. In the 2000 or so engineering undergraduate courses available, fewer than 5% offer modules that relate to systems engineering. In postgraduate study there are fewer than 10 courses that address systems engineering as recognised by INCOSE with only 3 courses covering elements of level 3. One university offers a comprehensive undergraduate programme which essentially addresses level 2 with some introduction to level 3.

There is a number of in-company schemes which are mainly aimed at topics in the SE process such as requirements capture. A few courses are comprehensive and have substantial coverage of the SE process, but as with the US there is no coverage of the required analysis techniques. Since mainstream engineering courses within the UK avoid teaching these techniques, many system engineers are ill equipped to undertake their work effectively. For some time now staff from other areas (from OR, mathematics and physics) are partially filling the void and becoming systems engineers but without the engineering and systems science

foundation. Although it should be recognised some of the most competent system engineers in the both the US and the UK emanate from either O.R. or physics

It is estimated that the UK produces less than 50 competent systems engineers per year. With perhaps only 10 engineers fully conversant with level 3. Mainland Europe fairs a little better with SE being a much sought after discipline within France, Germany, Italy, Spain, Scandinavia, and the Benelux. The longer degree programmes ensure that more elective subjects that relate to SE are available to students and some well focused post graduate programmes are available. However, there are few graduates from mainland European universities capable of dealing with level three systems. The remainder of European countries are in a worse state than the UK.

## **Conclusions and Recommendations**

### *Conclusions*

The following conclusions can be drawn:

- The value-added element in technology business is to have the capability to design and implement complex systems or networks of systems. Indeed the socio-economic future of the UK will become increasingly dependent on such system functioning correctly within an agreed economic framework.
- If the UK is to remain a key global technology provider then it must ensure that it develops and retains the skills for dealing with complex systems or networks of systems as a 'prime systems integrator'.
- Systems engineering is the key discipline for dealing with complex systems or networks of systems and it is being largely ignored by universities, industry, the engineering institutions and government. Undergraduate courses are still biased towards single engineering disciplines (with a few exceptions) with the belief that graduate engineers will be able to handle system issues even though very few of the required analysis techniques are taught.
- In-house SE schemes are necessarily process focused and only recognise the need for analysis. INCOSE literature focuses on process but has a rich body of knowledge that covers the majority of know-how required by system engineers – currently this body of knowledge lacks structure and is not recognised by universities as being relevant.
- A SE education model needs to recognise that different levels of system engineer are required in order to ensure that there is a balance in engineering training. A three-level model has been proposed; level 1 concerns with systems that reside within a single engineering discipline, level 2 concerns multi-engineering disciplines, and level 3 concerns engineering that has strong interfaces with socio-economic, socio-technical, political and environmental systems.
- At all levels of the three-level model there is a need for a comprehensive education in analysis and modelling techniques with more emphasis on policy, social issues and economics for levels two and three.
- The US is currently the world leader in SE education resulting in the US winning some 90% of the large 'system integrator' projects world wide.
- If the UK is to compete it will need to change its attitude towards SE and take positive steps to improving undergraduate and graduate training in line with the suggested three-level model.

### ***Recommendations for the RAEng***

Clearly this situation must be addressed with some priority. It would be a tall order for the RAEng to expect that its VP ISD Scheme could change the course of systems engineering education in the UK. At best it could help change the perception of engineering schools/faculties of systems engineering. The problem is much more systemic and needs to be tackled strategically with government. Government needs to be convinced that it is essential for the UK to maintain its position in the technology premier division if the economy is not to be adversely impacted. Once done, the universities can be approached but most have a cash crisis and funding will be required. Four key recommendations are made:

- The RAEng to formulate a policy for systems engineering in the UK.
- A formal study is undertaken for government into the need and future of systems engineering in the UK with a clear path for implementation with costs.
- Open a dialogue with universities on the need and options for SE education.
- Use the VP scheme to raise awareness through case studies, and to assist with the development of targeted courses for SE study.

The RAEng should work with the engineering institutions and INCOSE to formulate a national policy for SE.

### **References**

- Blanchard B S and Fabrycky W J, '**Systems Engineering and Analysis**', Chapter 1, Third Edition, Prentice Hall, 1998.
- Wiener N, '**Cybernetics**', John Wiley and Sons, New York, 1950.
- von Bertalanffy L, '**The Theory of Open Systems in Physics and Biology**', in Systems Thinking (pp 70-85) Penguin, Harmondsworth, 1950.
- Ashby W R, '**An Introduction to Cybernetics**', Methuen, London, 1956.
- McDermid J. et al. '**The Discipline of Systems Engineering**', Internal RAE, February 2003.
- Mil Std 499A
- Jackson M C, '**Systems Thinking: Creative Holism for Managers**', John Wiley and Sons Ltd, London, 2005.
- Forrester J.W. '**Industrial Dynamics**', Cambridge Press MA, 1961.
- Checkland P. '**The Development of Systems Thinking by Systems Practice – A Methodology from and Action Research Programme**', in Progress in Cybernetics and Systems Research, Vol V, Hemisphere Publications, Washington DC, 1975.
- Hitchins D. '**Putting Systems to Work**', John Wiley and Sons Ltd, Chichester, 1972.
- M'Pherson and Stupples, '**Systems Engineering Analysis**', Eurocontrol Conference, March 1997
- Stupples D.W. '**Applications of the Systems Approach to Defining Major Projects for Successful Implementation**', City University, London, 1975.
- ISO 15288. '**System Life Cycle Processes**', [www.15288.com](http://www.15288.com), 2002.
- Major Project Association. '**The Smart Procurement Initiative – Faster, Cheaper, Better**', MPA, January 2001.
- NAO, '**Ministry of Defence, Major Projects Report 1999**', HC613 Session, July 2000.
- INCOSE Website, [www.incose.com](http://www.incose.com).
- Rhodes D and Hastings D, '**The case for Evolving Systems Engineering as a Field within Engineering Systems**' MIT Engineering Systems Symposium, March 2004.

Miser H J and Quade E S, '**Systems Analysis**', in 3 volumes, North Holland and John Wiley and Sons, 1985 – 1988.

Hitchins D, '**Putting Systems to Work**', John Wiley and Sons, Chichester, England, 1992.

Adcock R D, '**Systems Engineering Education**', Awaiting publication, 2004.

Fabrycky W, '**Study Results for Systems Engineering in the US**', Lecture at MIT, 2003.