# Systems of Systems — An Opportunity for Engineering and Society

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***Abstract:*** *Criticisms of engineers, as not being adequately aware of global political and societal issues, not understanding cross and multicultural issues, and, not understanding international business, is noted. The education of engineers is also criticised as not using a project approach rather than a more general problem solving approach. Current project models in use in the industry are examined for possible models for use and a relatively new model of system of systems (SoS) is focussed on. SoSs address the integration of independent autonomous systems. They provide paradoxes and experience of these will develop engineers. Top-down requirements of SoS, rather than the bottom-up approach of systems engineering, brings engineers more into the public arena. The architecture of the SoS model may cope with the complexity of managing response to projects such as climate change; its breadth and greater prominence may attract a broader range of participants to engineering.*

## Introduction

This paper briefly examines some problems that have been recognised with engineering education from a review of literature basis. The behaviour of some engineers in society is also examined. The paper then goes on to examine project models both used and potentially for use in engineering courses and especially the system of systems model (SoS). The author is separately conducting case studies on SoSs. The SoS model is proposed as being appropriate to address some of the deficiencies of engineers.

## Issues with engineers and their education

Kelly (2002) reports on behalf of the US National Science Board, that US Engineers 'are accorded not only less prestige than doctors, scientists and teachers, but also less prestige than ministers, military officers, policemen, and members of congress'. Engineers are 'perceived as pragmatic contributors to society – more so than technicians - but are less attuned to societal issues than are scientists'. Such views may inhibit recruitment of engineers.

Nair and Patil (2009), writing from a perspective of engineering education at Monash University, report that Patil and Codner (2007) found that global competencies required by engineers include: awareness of global political and societal issues, understanding of cross and multicultural issues, and understanding of the international business, the economy and world market.

Haralampides (2006) comments on the 'impoverishment' of engineering through small numbers of women practising engineering and concludes that 'cooperation and trust, connected, holistic thought, joining feeling and thinking, increased social responsibility' would support more women joining the profession, which she sees as contributing benefit to the practise of engineering.

Trevelyan (2008) points out that the majority of engineering education is based on a model of engineering practice represented by technical problem solving and design, which represents a misalignment between engineering education and practice and does not address the fact that engineers interact with other people. However, it is not only the academics who are at fault because many practising engineers tend to view human interactions as necessary but chaotic, unproductive, and time wasting interruptions that get in the way of 'real engineering work'. This is reinforced by the author's experience in proposing the Centre of Engineering Leadership and Management to Engineers Australia's Congress and Council, which was accompanied by some engineering academics who asked why should Engineers Australia go to such bother for people who did not want to be engineers any longer. This was in 2001. Attitudes in some may not have changed.

Trevelyan (2008) points out that the technical problem solving model represents the early stages of an engineering project in terms which are too simple.

Mills and Treagust (2003:3), in an examination of engineering education, point out, among a range of issues, that:

- "Engineering curricula is too focused on engineering science … without providing sufficient integration'.
- 'Programs need to develop more awareness amongst students of the social, environmental, economic and legal status that are part of the reality of modern engineering practice'.

They go on to conclude that problem based and project based approaches have been very successful in medical education and are also successful in engineering education. They find that students prefer problem based courses at McMaster and Monash universities. They comment that, while problem based approaches require students to solve problems outside their experience, many practising engineers are required to solve problems with incomplete data and in which their clients, government and the general public are in conflict (p4).

They compare the benefits of problem based versus project based engineering education, pointing out that project based education is directed to the application of knowledge, whereas problem based learning is focused on the acquisition of knowledge. After considering a number of universities in Australia and elsewhere, they see project based education as being more likely to be adopted than problem based engineering education (p13).

## Project based models

Given that project based engineering education has a degree of support, an issues arises of an appropriate model to underpin such projects. The traditional model most practitioners and academics recognise includes identification of project requirements, development of the engineering solution and then delivery. Traditionally the project structure of Engineering, Procurement and then Construct (EPC), or Design Bid Build (DBB) was used (Abi-Karum 2005). Essential aspects of this model, often overlooked, are the partial refinement of the structure of the project, through the principal organising finance for the project, and usually seeking government approval, and then, if EPC is being used, briefing an engineering solution, procuring a deliverer and supervising construction or production. Throughout the last three decades Design and Construct (D&C) has gained in popularity (Konchar and Sanvido, 1998), although Design and Construction was effective in the mid 1980s (Ireland, 1985). More recently Alliance Contracting (Grynbaum 2004 and Hauk, Walker, Hampson and Peters, 2004) and Public Private Partnerships, or Build Own Operate and Transfer (BOOT) has been successfully used for large infrastructure and some defence projects.

It needs to be recognised that each of these project delivery systems include two related, but seldom discussed, aspects:

- Finance, government approvals and other structural issues are resolved before the project is seen as a adequate to commence as a project, and then proceed to a delivery mechanism.
- The delivery of the project is fairly top-down, with the project manager organising suppliers and subcontractors to contribute to the delivery, and dealing with others, such as the community and the local authority, as stakeholders.

While some engineers are involved in initiating projects, using PPPs or BOOT approaches, and thus are involved in assessing community and business needs, the predominantly used model keeps engineers away from this role. It therefore seems reasonable to conclude that this separation of engineers from these aspects may have an influence of the community's perception of engineers. It may also be concluded that the model of engineers not usually being involved in the front-end of arrangement of finance and government approvals, may influence academics to choose a restricted project model for assignments, if one is chosen at all. Following a realistic project model will improve the successful achievement of project objectives in practice (Thomas & Mullaly 2008).

## Systems engineering

Systems engineering provides a design integration methodology which underpins most complex engineering. As most engineers realise, many of the everyday engineered products, which society uses, such as vehicles, telephones, ships and planes, have been developed using systems engineering. A key role for an engineer is the design and production of an artefact which satisfies a series of requirements. This includes both the initial design and the demonstration of the capability through testing. Blanchard and Fabrycky (2005) define a system as a set of interrelated components working together towards some common objective. Systems obey the principles of general systems theory and are understood by reductionist approaches of breakdown, in which each of the subsystems are designed to satisfy the set of requirements. Keating, Padilla and Adams (2008) point out that system requirements must be: Specific, Traceable, Realistic, Measurable and Stable. Hence systems engineering is narrow and deep and only addresses community issues and stakeholders in a limited way.

## System of systems

However, system of systems (SoSs), the integration of independent autonomous systems, provides an opportunity for engineering systems to include a broader cross section of the community than does systems engineering. This model is currently being used for complex defence projects (Dahmann 2009), transport systems (DeLaurentis 2009), and electric power distribution systems (Korba and Hiskens 2009).

System of systems projects are a group of networked nodes and instead of being a hierarchically focused organisation, with a number of subelements. Sauser and Boardman (2009) report definitions of systems of systems as ‘System of systems are large scale concurrent and distributed systems that are comprised of complex systems’.

System of systems:

1. Are composed of systems which are independent and useful in their own right;
2. Have managerial independence;
3. Are geographic distributed;
4. Display evolutionary development;
5. Show emergent behavior (Maier 1998).

The independence and autonomy of SoSs create both the challenge and opportunity. Examples of SoSs include the internet, a taxi service, in which all the cabs are autonomous and independent, and if one drops out another will take its place. The integrated power grid supplying eastern Australia is another example, with each generator having the autonomy to be in or out. Interoperability and some degree of conformity are assured because power which does not conform is not accepted. Also inputs and outputs are balanced every few milliseconds. Operation of an airport is another example.

It should be recognised that system of systems will not be used for the majority of projects. The traditional approach will predominate. However the SoS approach does provide a model which can extend students in understanding of the community and business.

## Some properties of system of systems

Sauser, Boardman and Gorod (2008) outline paradoxes of SoSs as shown in Table 1. The need of system of systems to partly diverge toward system of subsystems is recognised.

The tension represented in Table 1, of attempting to satisfy conditions at extremes, leads Gorod, Sauser and Boardman to respond by discussing the concept of a *holarchical* view in which practitioners live with the paradoxes of *Autonomy, Belonging, Connectivity, Diversity and Emergence.*

In the author's view, groups, in being able to live with these paradoxes, require:

- Developing skills in understanding the context of the decision; the importance of context is strongly emphasised by Moffat (2003);

| *Systems of Subsystems* | *Paradox* | *Systems of Systems* |
|---|---|---|
| Conformance | *Autonomy* | Independence |
| Centralisation | *Belonging* | Decentralisation |
| Platform Centric | *Connectivity* | Network Centric |
| Homogeneous | *Diversity* | Heterogeneous |
| Foreseen | Emergence | Indeterminable |

**Table 1 System of systems paradoxes**

- Building-up the ability of individuals and groups to make decisions on whether they need to be independent or conform; Snowden and Boone (2007), in examining complexity, outline a process of ritualised dissent, in which in considering a decision on a particular issue of whether to conform or be independent, half of any group is assigned the role of presenting the case for one decision and the other half of the group concerned is assigned the role of arguing against the decision; a broad range of individuals in groups assists, for example Kirton's innovators and adaptors (1989);
- A set of values needs to be articulated on which members of groups may fall back in understanding these paradoxes;
- Finally, underpinning each of the above three points, is the need to build the self esteem of individuals and groups such that they can consider contrary viewpoints to those they hold themselves, and assess the viewpoints without feeling threatened by the difference; part of this is being able to cope with being in a small minority.

A question arises with regard to the paradoxes in Table 1, in that, if a group takes the wrong decision, an example of which could be being conformist when they should be independent, being centralised when they should be decentralised, or being platform centric when they should be network centric, do unfortunate forces emerge? Emergence is chosen because many see emergence as the critical issues of system of systems (Sauser & Boardman, 2009).

## Focus on top-down requirements

System of systems has top-down requirements which is in contrast to systems engineering (Keating, Padilla and Adams 2008). SoS requirements are:

- Establish the Purpose for the SoS.
- Establish SoS Boundaries.
- Establish Relevant Stakeholders and Contextual Issues
- Establish Metasystem Representation.
- Establish Coordination, Integration, & Standardization.
- Establish Design for Dealing with Emergence'.

Such a top-down approach means that system of systems is raised to the business and project strategy level rather than focusing on elements of capability, such as quality, accuracy, reliability and the like. Obviously these bottom-up elements are very important but engineers directly focusing on strategy and mission success, bring engineering much more into the boardroom.

## Architecture of system of systems

An issue to be recognised in the operation of system of systems is the existence of levels of operation, and that different levels of each member can have different characteristics. DeLaurentis (2009) both separates functional aspects of an organisation, into Resources, Operations, Policy and Economics, as well as separating the levels into at least five. He comments that the behaviour of the organisation is driven by the $\alpha$ level, which is the most basic, but also by the structure and interaction between levels $\beta$, $\chi$, $\delta$ and $\gamma$. He raises the question of how does observed or preferred behaviour at the upper levels (eg at γ level), affect behaviour at the lower levels (α and β)? Addressing such questions will develop engineering undergraduates.

In a further paper, DeLaurentis and Crossley (2005) define the components of a system of systems as shown in Table 2.

| ‘Category | Description’ |
|---|---|
| ‘Resources | The entities (systems) that give physical manifestation to the system-of-systems’ |
| ‘Stakeholders | The non-physical entities that give intent to the SoS operation through values’; these can represent all the major players. |
| ‘Operations | The application of intent to direct the activity of physical and non-physical entities’; |
| ‘Policies | The external forcing functions that impact the operation of physical and non-physical entities’ |

**Table 2 Lexicon for describing System-of-Systems**

There is no reason why finance, business goals, community attitudes cannot be added to DeLaurentis' group of elements.

DeLaurentis and Crossley's model (2005) can be used as a broad representation of system of systems, as shown in Fig 1.

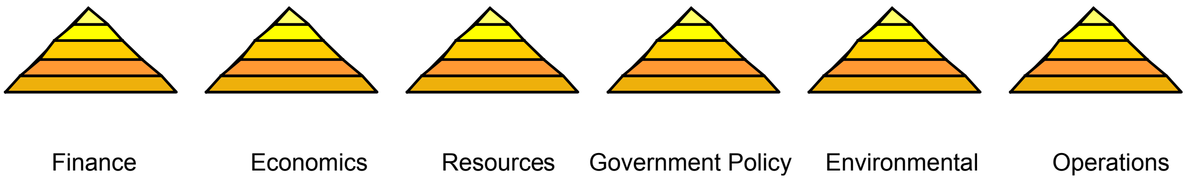


**Fig 1 DeLaurentis' and Crossley's model project architecture extended by the author**

Such a model could represent the coal miners, the power generators, representative departments of government, federal, state and local, and other stakeholders, relevant to climate change.

Morganwalp and Sage (2003) present a consistent but slightly different viewpoint.

SoS projects have breadth, allowing a range of partners and entities at the plenary level, which traditional construction, defence, and manufacturing projects, which are contracted with a delivery entity, do not have.

Given the fact that these elements of project architecture strongly embed human aspects and integrate them with technical aspects, this approach could contribute to healing the cleavage between the arts and sciences. The British novelist CP Snow introduced the concept of there being two cultures, based on the arts and the sciences, way back in 1959. However, the French academies of arts and sciences go back even further and were both formed in the 17th century.

## Conclusions

The fact that engineering may not receive the public recognition it deserves, although engineered products are ubiquitous, is noted. It is also recognised that engineering education does not generally use specific project models but often adopted a general problem solving model, which was less effective. System of systems projects provide a better model; they require a very different approach to projects generally and to traditional systems engineering projects in particular. The SoS model requires a broader cross section of stakeholders to be included in the project team, it requires project team members to cope with paradoxes, which in itself requires using staff with a set of broadly defined values to fall back on and self-esteem to exercise difficult judgements. The need to develop top-down requirements of project strategy and the need to use such an approach on complex major societal projects will bring engineering out of the backroom and into the boardroom. SoSs also require engineering practitioners to have a better understanding of community values. Finally SoS methods require much less use of traditional top-down authority and a need to cope with dissent. Engineers consistently taking up such a leadership role in society will bring engineering into the public's attention which will enhance the respect of the public for engineering. Possibly system of systems will even contribute to integrating the two cultures of science and the arts.

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