Diversity as a determinant of system complexity

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Abstract: Diversity of viewpoint is discussed as a major determinant of system complexity – in particular as affecting project complexity during design, development, manufacture and roll-out. The viewpoints of particular interest are those arising from diversity of implementation technology, and from multiple specialist engineering disciplines. The paper discusses the historical treatment of complexity in design offices, the challenge of diversity to a project, and its impact on the formal and informal organisation of the project, and on individual cognition. Conclusions are drawn for system acquisition and for design and development approaches. Metrics for the challenge posed by the diversity of a project are needed, so that organisational capability can be aligned with project need – for project processes in particular. Complexity-as-diversity makes demands on the organisational climate and the treatment of multiple (potentially conficting) sources of bad news. Interactive visualisation is considered to reduce cognitive demands, support individual and team decision making, and to have an effect equivalent to reducing complexity.

Keywords: systems engineering, diversity, visualisation, cognition, culture.

Introduction

Thesis: If we take the primary task of systems engineering to be :"To identify, realize and maintain the requisite emergent properties of a system to meet customers' and end users' needs" (Hitchins, 2001), then in crude terms, the more emergent properties we need to manage, the more complex the task. This paper examines the complexity of the task facing the project as a whole, the task facing teams within a project, and the task facing the individual designer or specialist. Diversity relates closely to the number of emergent properties. A system can be considered as a way of looking at the world, and needs a viewpoint and an observer.

The overarching (or, less imperiously, underpinning) systems engineering standard, ISO/IEC 15288:2002 'Systems engineering - system lifecycle processes' represents a major international achievement in codifying, normalizing and harmonizing the actions of contributors throughout the system life cycle. On this basis, systems engineering can be considered to have four sets of processes operating through the life cycle. These are shown below in Table 1.

<table>
<tr><td colspan="210">Agreement processes</td></tr>
<tr><td colspan="105">Acquisition</td><td colspan="105">Supply</td></tr>
<tr><td colspan="210">Enterprise processes</td></tr>
<tr><td colspan="42">Enterprise environment management</td><td colspan="42">Investment management</td><td colspan="42">System life cycle processes management</td><td colspan="42">Resource management</td><td colspan="42">Quality management</td></tr>
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<tr><td colspan="210">Special processes</td></tr>
<tr><td colspan="210">Tailoring</td></tr>
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Table 1 - Processes in ISO/IEC 15288 Systems engineering - system lifecycle processes

The technical processes will be effected by diverse specialist viewpoints. The viewpoint of the project processes is directly concerned with integrating this technical diversity. The enterprise and agreement processes are less affected by technical diversity and so are not discussed further. Managing emergent properties or viewpoints requires 'requisite imagination' (Westrum, 1998). Increasing diversity increases the number of ways in which things can go wrong, and the demands on requisite imagination and its vigilance. The job of representing a viewpoint on a project is termed a role. The role-viewpoint mapping may or may not be one to one.

Engineering view of complexity: The traditional engineering view of complexity is that it is driven by parts count, perhaps factored by the number of interfaces (e.g. Meyer and Lehnerd, 1997). The software equivalent is Source Lines of Code (SLOC). Capers Jones (1996) has shown the non-linear impact of complexity measured this way (see Table 2).

Size, function points	Size, KLOC	Coding %	Paperwork %	Defect removal %	Management and support %
1	0.1	70	5	15	10
10	1	65	7	17	11
1,000	100	30	26	30	14
1,000	100	30	26	30	14
10,000	1,000	18	31	35	16

Table 2 - Changing Types of Effort as Programs Grow in Size, Capers Jones (1996)

However, we would propose that it is likely that SLOC is confounded with diversity – it is plausible that larger systems have more viewpoints – and that diversity has an influence that is at least as great as that of parts count or SLOC. Certainly it is possible to have built artefacts of comparable complexity-as-parts-count with very different complexity-as-diversity, and this has not been recognised in engineering circles where the emphasis is on ease of mass manufacture rather than ease of design.

Driver for diversity: "Today's systems mostly draw their high levels of functionality and performance by combining system elements that contribute widely different functionality, and frequently employ distinctly different implementation technologies. A key goal of systems engineering is, therefore, to achieve novel product or service characteristics that appear to have come from a single, homogeneous entity, yet have actually been achieved through a carefully-crafted bringing-together of intrinsically dissimilar system elements." (Arnold et al 2002).

Simple example: A simple example was provided by Williams (2001) on the rail-wheel interface in the railways. The rail is part of the civil engineering of the track. The wheel is part of the mechanical engineering of the propulsion and suspension systems. Enabling the two disciplines to understand each other's requirements and constraints has led to dramatic improvements in both cost and safety.

Structure of paper: Some practical and theoretical background is provided on the management of complexity. The basis for the rest of the paper is that the challenge of diversity can be addressed by three complementary approaches:

o The use of systems engineering processes to develop a common picture among diverse roles to enable trade-offs to be made at a project level with mutual understanding.

o Considering the organisational climate and its ability to address interpersonal communication among diverse roles.

o Enabling specialist engineering to reach further "into the design" itself. This approach needs to meet the decision making and cognitive constraints of the individuals concerned. The proposal is that interactive visualisation supports this.

Some conclusions are offered.

Background – the practical management of complexity

This section is a precis of the historical evolution of specialist viewpoints, taking the last 50 years or so as the time frame. Fifty years ago, the number of specialists on a project would be limited to a few key disciplines such as aerodynamics, structures, naval architecture. Beyond that, there would be fairly general viewpoints of electrical and mechanical engineering and the like. At the level of a draughtsman and non-graduate engineer, considerable generality would be expected.

The viewpoints discussed here are considered to arise from two sources:

- Diversity of implementation technology, e.g. hardware, software, people.
- Diversity of specialist engineering – the "–ities" such as usability, safety, reliability, Electro-Magnetic Compatibility (EMC), supportability, security. These viewpoing are also known as coherence requirements.

As something of a caricature, there was a time long long ago when technology and customer demand were sufficiently stable that the implementation of the specific technologies and meeting the specialist engineering needs of project stakeholders could be achieved by 'good design practice'. A designer could be expected to design for safety, maintainability, cost etc. with an adequate understanding of the materials, their fabrication etc.

This breadth of vision became impossible for complex systems (for reasons worthy of investigation), and so specialist viewpoints gained representatives on projects. Designers became split up by increasing diversity of implementation technology; electrical, mechanical, software etc. Integrating these implementations to meet the needs of specialist engineering became problematic. The specialist engineering disciplines are now well behind the curve; all they can do is react to a design once it has reached a level of maturity. The project manager sees a large part of his design budget going to people who do nothing but complain when it is too late. The truly cynical have pointed out that it is rare for coherence requirement owners to behave in a coherent manner and co-ordinate their complaints, or indeed to realise that such complaining is an important part of their role.

The response to this situation has been to 'divide and conquer' – to set up Integrated Project Teams (IPTs) that each deal with a part of the system. If the interfaces between the parts are clean, and the system-level emergent properties are addressed, this can work. However, there are some issues that are still to be resolved:

- The implementation-specific technologies still need an integrated view of the IPT scope of supply. This doesn't happen by itself.
- The specialist engineers are still behind the curve.

There is the real potential to be much closer to the design, but there are some obstacles to be overcome:

- The specialist resource is now divided among independent competing demands (perhaps several IPTs per individual), so you still have only half of them turning up.
- The specialist engineering community is now in the game of building big computer models and databases. These provide a firm basis for the discipline, but there is a direct conflict between building the model and being party to critical early design decisions.

Theoretical orientation

This paper is essentially practical in orientation, but does draw on a number of theoretical bases. This section provides a brief outline of the theoretical underpinning for the paper. Theory has been used only insofar as it affects the management of diversity and complexity.

Role of complexity theory: Addressing complexity is recognised as important to the future of engineering, and many authors have been drawn to complexity theory as an avenue of research (e.g. Bullock and Cliff, 2004). This paper considers that analogies with natural systems need to be treated with caution – there is nothing very natural about systems engineering in practice. Firstly, there is the option of predetermination '*reculer pour mieux sauter*' cf. Elster (1979). Secondly, it could be argued that project-based systems engineering is an explicit, and indeed unwelcome, alternative to the 'natural' evolution of an enterprise. If a system can be acquired or delivered as normal business, without a major project-based structure, then probably so much the better (so long as the necessary processes happen).

Role of systems theory: The relationships between systems theory, systems engineering and systematic engineering can be somewhat fraught. The view taken here is that systems enginering as set out in ISO/IEC 15288 captures much of the necessary systems thinking, which can then take only an indirect role in considering the treatment of complexity.
Systems engineering and business excellence: The tenet behind the systems engineering presented here is that business excellence is the result of professional competence and process capability, as shown in Figure 1 (based on Arnold et al. 2002).

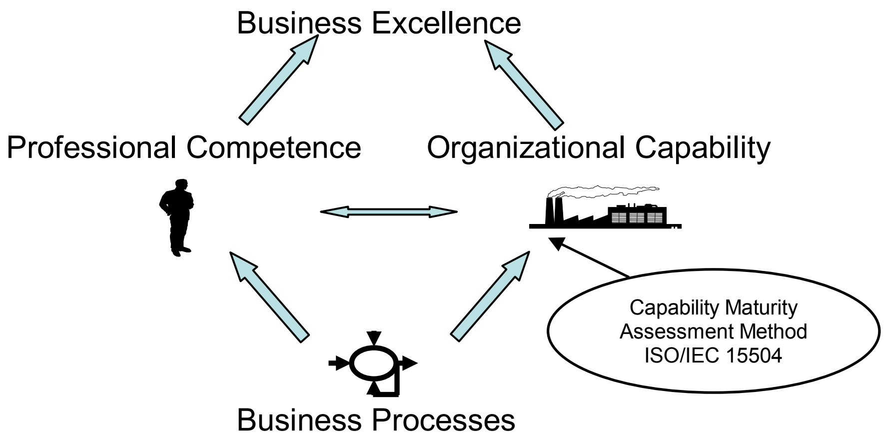

Figure 1 – Achieving business excellence

Requirements and design: It has become established in many systems engineering communities that it is much more effective to discuss evolving requirements than to discuss the emerging design. Gause and Weinberg (1990) have shown the benefits of doing this. The authors' experience is that project discussions on requirements are very different in nature from discussions of the design. However, there are grounds for saying that better use of the design is essential to individuals wrestling with system complexity. Firstly, the design is a large part of what the customer is paying for and getting it right is of some importance. Secondly, reviewing the design is where trade-offs between viewpoints find their final resolution. The resolution of requirements trade-offs is a separate issue to the resolution of design trade-offs.
Process modelling and assessment: One of the distinctions between process models and methodologies is the ability to make assessments of an organisation. The five parts of ISO 15504 include resources to support Process Improvement (PI) and Process Capability Determination (PCD) (also known as Capability Evaluation) (the most relevant parts are cited). PCD is taken as being a valid measure of an organisation, and, used appropriately, provides an indicator of the organisation's ability to meet the demands of complexity, including diversity.

ISO/IEC 15288 is concerned with the life cycle of a system down to the level of element detail where individual implementation technology practices can be applied – technologies such as software, electronics, biology, hydraulics, mechanics and a host of other science and technology disciplines, including human sciences. The following aspects of system engineering are required if the diverse roles are to communicate effectively:

- A common view of the life cycle (though each implementation or speciality will have its own variations).
- An ability to speak at a project level; this appears to require a process view. Specialist tools and methods are needed by the specialist, but cannot be understood at a project level. Overlays to ISO 15288 (such as ISO PAS 18152, SSE-CMM, ISO 12207) are required.
- A working set of 'project processes' from ISO/IEC 15288.

Formal management of diversity by Systems Engineering

Genius is not the solution: The role of individual competence and professionalism is not to be under-estimated. At the level of software teams," "Good tools typically increase productivity by 25%-35% and good processes can increase productivity by 50%-100%; but the best people are typically 10-20 times more productive than the average, and as much as 100-200 times better than the worst." (Yourdon, 1995). However, it is contended that at the level of project processes, solutions that rely on very high levels of system architect professionalism (e.g. RAE/BCS, 2004) will not work for systems of even moderate complexity. "System design in its simplest embodiment is dependent on a convergence of specialized information from multiple technology domains which contribute integrally to either the function and embodiment of the system or to the processes needed to manufacture it. It is unlikely that a single individual today can be a master integrater of many technologies, let alone competently keep abreast of the developments in a single field." (Boff, 1987). The role of the 'maestro' in setting culture and standards (Westrum, 1998) is recognised. However, if complex engineering is to continue to grow, then it cannot depend on the ready availability of such people.

Babel is not an option: "While precise communication among specialists within a given technology can be a tedious process, it pales by comparison with the difficulties involved in attempting precise communication among specialists from across multiple disciplines. Specialized technical domains typically evolve specialized languages in order to communicate ideas and data unambiguously within a given frame of reference among specialists. Hence, in order for specialists to communicate effectively across domains, they must find a common frame of reference. The larger the number of individuals involved or the greater the differences in domains of expertise, the more difficult it will be to develop a common frame of reference and the more likely the potential for misunderstanding in communications." (Boff, 1987). Figure 2 illustrates the difference between specialised tools and methods, which can be understood properly only by the relevant role, and the overlay process models that mediate between these and project level system engineering processes.

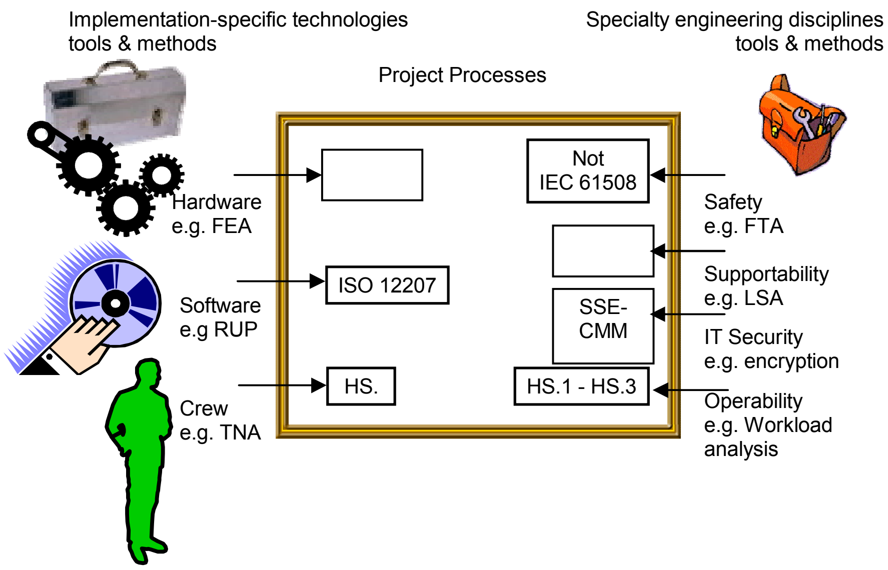

Figure 2 - Overlay process models mediate between specialists and the project to provide a common picture. (The HS.1 – HS.4 refer to processes in ISO PAS 18152)

From the viewpoint of operability (or Quality In Use[1]), the author's experience is that the specialist community (variously terms Human Factors, HFI, HSI, HCI, usability) has split in response to the proposal for overlay models and the prospect of Capability Evaluation. There is a group of practitioners that

[1] Defined in ISO 9126:2000 as "The the capability of a system to enable specified users to achieve specified goals with effectiveness, productivity, safety and satisfaction in specified contexts of use."

recognises the potential very enthusiastically, and there are other practitioners and the bulk of researchers who do not see the relevance. Splits of this sort are likely in most such communities.

Project processes: The Project Processes in ISO/IEC 15288:2002 are concerned with managing the resources and assets allocated by enterprise management and with applying them to fulfil the agreements that the organization enters into. They relate to the management of projects, in particular to planning in terms of cost, timescales and achievements, to the checking of actions to ensure that they comply with plans and performance criteria, and to the identification and selection of corrective actions that recover progress and achievement. The number of technical viewpoints to be managed has a direct impact on the ease of achieving project process outcomes. The view in the systems engineering community is that the way to meet the demands of greater diversity is to increase process capability levels for these processes.

Matching challenge and capability: There are two points to make about the extent to which project processes need to be performed in relation to system complexity. Firstly, there has been some work (Benediktsson et al) relating process maturity to Safety Integrity Level (SIL) requirements i.e. there is a link between the performance demands of the system of interest and the process capability requirements. Secondly, there ought to be a more general link between the complexity-as-diversity demands of a project and the process capability of the enterprise. Developing metrics to measure the diversity demands would not be particularly difficult and could be aligned to the PCD of the organisation.

Informal management of diversity; culture and teambuilding

The use of process models provides a way of addressing the formal organisational aspects of diversity. The informal organisation needs addressing as well.

Social practicalities: The Australian monthly barbeque, or a night out for a curry in the UK, seems to be a powerful way of getting people to talk to each other and build a common picture of the project. The demise of stratified canteens in UK engineering removed lunch as a means of achieving this. Social engineering can be cheap and effective. The more complex the project, the larger the restaurant bill. The number of interactions between viewpoints (a good indicator of the complexity of the social system and the demands of diversity) rises factorially rather than linearly with the bill. The author was part of a Prime Contract Office that was assembled and chastised by the project manager “I want to see more people sitting on desks and chatting”.

Culture and dealing with bad news: Or, “How do you tell a mother that her baby is ugly?” The various viewpoints inevitably have to be the bearers of bad news. The treatment of bad news is a feature of Westrum’s (1998) climates for information flow. The *pathological* organisation tends to suppress or encapsulate anomalies. *Bureaucratic* organisations can ignore or make light of problems and not seek problems out. The *generative* organisation encourages communication with a culture of conscious inquiry. The differences in their ability to manage diversity are apparent.

Team decision making and shared situation awareness: It is argued that a shared interactive virtual model of the system-of-interest is a major support to the development of a shared mental model, necessary for teamworking (Zsambok and Klien, 1997). So far as is known, this approach to the value of visualisation has still to be proven or properly researched.

Demonstration and argument: Given the problems of jargon referred to above, the explanation of specialist bad news can be a challenge to the role responsible, and can lead to the reversal from project scrutiny to specialist scrutiny e.g. as occurred with the Challenger Shuttle ‘O’ rings. The ability to use an interactive visualisation to demonstrate an issue enables non-technical communication to be made ‘on the fly’ rather than have technical communication (probably subsequent to the review or meeting) suppressed or ignored.

Organisational impact of visualisation: Experience at the Digital Design Studio (DDS) with the application of advanced visualisation to car design has been that the effect has been equivalent to reducing the complexity of the artefact. It would appear that the reduction in individual cognitive demands (discussed below) enables the project to be run as though it were simpler.

Complexity and individual cognition

Complex systems pose difficulties to those individuals representing one or more viewpoints. The mountain of documentation goes beyond the point where it can be considered readable (the author has worked on a project with well over 1000 databases). A specialist saying “it’s in our database” is quite inadequate. Communicating specialist information is a major undertaking. There is thus a problem in identifying areas with potentially conflicting (or synergistic) requirements and constraints. With current project arrangements, potential conflicts between viewpoints are found early by social networking or by lucky searches through databases. By the time a conflict has been found in the model of the built artefact, potential re-work and conflict resolution has already built up (e.g Whyte 2002, p 63, ‘Identifying errors and clashes’). It is proposed that better visualisation will allow group processes to operate in a way that gives more lead times on such conflicts.

The experienced designer: The expertise of the experienced designer needs to be recognised. Boff (1987) has characterised the expertise as shown in Figure 3. There have been many attempts in the expert systems era to capture this expertise within say a CAD system. These have been generally unsuccessful and a more promising approach would be to support this expertise and encourage its development.

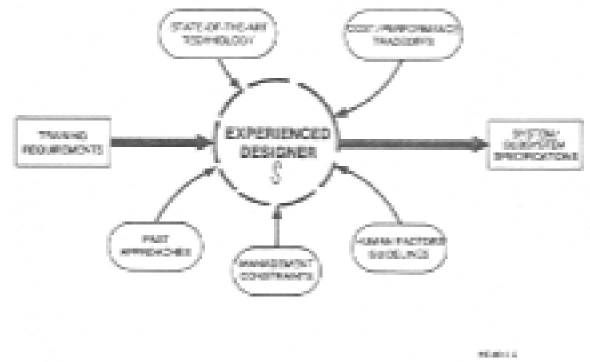

Figure 3 - Design Decision Process. Design requirements and specifications are determined by the subjective integration of a range of variables.

Naturalistic Decision Making: The proven way to capture expertise from experienced individuals and teams is the use of theory and practice from Naturalistic Decision Making (e.g. Zsambok and Klein, 1997). Resources have been developed to assist learning, training and decision support. Although extensively applied to the users of complex systems, there has been virtually no application to the designers of such systems. A promising area of application is the expertise associated with experienced designers and a review of the built artefact (at whatever stage of design/manufacture). Experienced designers with an established viewpoint (or possibly more than one viewpoint) have well-developed sets of cues that can be used to identify successful or problematic designs. One of the authors had the rewarding experience of developing synergy between the viewpoints of ease-of-use, ease-of-maintenance and ease-of-manufacture on a complex system. We argue that good interactive visualisation provides more and better cues to support such expertise. In particular it supports the development of synergistic what-if exploration.
“It’s generally accepted that visualization is key to insight and understanding of complex data and models because it leverages the highest-bandwidth channel to the brain. What’s less generally accepted, because there has been so much less experience with it, is that IVR [Immersive Virtual Reality] can significantly improve our visualization abilities over what can be done with ordinary desktop computing. IVR isn’t “just better” 3D graphics, any more than 3D is just better 2D graphics. Rather, IVR can let us “see” (that is, form a conception of and understand) things we could not see with desktop 3D graphics.” (van Dam et al 2000).

Current understanding of the value of Virtual Reality (VR) or visualisation: The short answer is that we know it works, but have not proved it yet. Further, the technical difficulties in achieving fluid multi-sensory interaction with large datasets are still being overcome, and so criteria for ‘good enough’ are not developed. van Dam et al (2002) have identified that fundamental research is still needed in this key area: “A new and highly interdisciplinary design discipline for creating compelling immersive environments, including visualizations. We cannot expect interdisciplinary design teams to evolve spontaneously or to invent their techniques from scratch each time. And environment design certainlycannot be left to traditionally-educated computer scientists, most of whom have no formal background in the creative arts and design or in human perceptual, cognitive and social systems."

Conclusions

The successful management of diversity offers the potential for huge gains in system outturn. This requires a combination of system engineering processes, a benign organisational climate and resources to support experienced designers. Achieving a common view by means of system engineering processes is not simple; Process Improvement is a hard road. Overlay models are still needed, and their widespread acceptance and adoption is some way off. The ability to perform Process Capability Determination offers a real incentive to improve and the potential to change the marketplace. Metrics for assessing the challenge posed by the diversity of a project would be of considerable assistance to project management, planning and contract award.

Interactive visualisation offers enormous potential. Whilst there are formidable technical challenges and still some key research issues, it is entirely complementary to Process Improvement. For a number of organisations, it offers the possibility of a quick win during the difficult stages of improving project processes.

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