Chapter 3
Architecting Complex Systems in New Domains and Problems: Making Sense of Complexity and Managing Its Unintended Consequences

Patrick Godfrey

Abstract. Complex problems usually span many technical domains. Formalised methods have been developed and reported to address defence, aerospace and ICT issues. Architecting approaches for other domains and problems such as for infrastructure do not yet exist. Design methods need to be developed to address these complex problems. This paper reports on an ongoing programme of teaching and *Learning Together* that is developing an approach for the creation of systems architectures. The paper reflects on the work of some 300 Research Engineers and students who have been engaged in designing complex sustainable systems. It characterises formative principles for architecting frameworks and indicates ways in which they can be used to deliver emergent properties and manage unintended consequences.

1 Purpose

Most of current Systems Architecting guidance focuses on architecture frameworks developed for specific defence and information system purposes (e.g. NAF, DODAF, MODAF, Zachman). Architecture frameworks are a means of dealing with system complexity. **While the principles behind these frameworks, and the domain-independent skills of the System Architect (ref e.g Rechtin, "Systems Architecting"), are widely applicable, Architecture Frameworks developed for specific applications areas are not.** However the need for complex systems design methodology is not restricted to these domains but challenges most industries. Some Factors driving this include:

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- The need for sustainability in the face of climate change and resource availability constraints
- Trend towards globalization of industrial markets, ownership and manufacture,
- Creation by the internet of constantly evolving global knowledge systems
- The interdependence of nations in the face of unintended consequences of human activity eg acid rain, nuclear disasters, ozone layer depletion.

The key issue is that all of these topics cut across traditional engineering and other disciplines, so no individual discipline's set of mental models and language is sufficient to manage the whole-system issues. The need to address this topic is becoming particularly urgent in the infrastructure sector in view of the economic importance attached to interdependency [1].

We will in this paper use the need to architect (design) sustainable complex systems as a means of developing a generic approach to designing or problem resolution in complex systems, for three related reasons:

1. We believe that what we learn from this approach can be abstracted for general applicability
2. Sponsored by the Royal Academy of Engineering UK, we have had a 5 year collaborative programme, with industry of teaching and learning, with this as its focus.
3. In addition about 25 % of the Research Engineers in the Systems Centre are undertaking collaborative research with industry concerning the sustainable development of infrastructure.

This paper abstracts some generic learning from the 300 Masters level and Doctorate level assignments and theses. Table 1 lists assignment topics from the Masters level unit. We are seeking to discover how students and researchers who have been introduced to the principles for architecting systems referred to above, learn to apply them to such a diverse range of systems problematiques.

Table 1 Examples of topics addressed in the Sustainable Systems Programme

Countries	Haiti, Afghanistan
Mega projects	3 Gorges dam, Crossrail, London, Olympics, Aircraft carrier, Airbus A380.
Managing resources	Polar Mineral Extraction, Rainforest, Carbon capture, coal fired Power stations, Hydrogen Infrastructure, Eating Meat, Euro currency
Institutions / companies	NHS, Supermarket Chain, BP, University
Leisure	F1 Motor sport, Rugby World Cup, Eden Project, Ski resort in Dubai, Rare earth metals
Infrastructure	Nuclear Power, Air Transport, Sustainable Tourism, An eco-district, Internet infrastructure

1.1 Stakeholder Alignment

To an ecologist a tree is a complex interaction of a wide diversity of organisms. To the structural engineer it may be much less complex because the calculation of loading from any branch is deterministic and calculable from the mass distribution within the tree. The complexity of a system can therefore be related to the viewpoint of the stakeholder and the purpose of the system. Sillitto [2] calls this 'subjective' complexity. Physical systems have no purpose in themselves, this is an attribute that is conferred by people. For example consider, a kitchen knife which could be part of a system to prepare vegetables but that same knife might be a murder weapon. The knife has not changed. It is the change in its purpose that changes the outcome.

Since a lot of the complexity in most systems arises from the intentionality of the people involved, most of whom may be influenced from within the system but cannot be controlled, it follows that an analysis of the different stakeholder viewpoints, to establish their interests and issues with the purpose of the system, provides an excellent starting point. It is often the lack of attention to this throughout the life of the project that is the source of unintended consequences.

In common with Zachman [3], we have found it useful to adopt a simple common language to describe both hard (physical) and soft (people) systems based upon Kipling's 6 natural language questions to define any system (or process): Why? How? What? Who? When? Where? [4] . The purpose (Why) is delivered by the means (How) operating on the other 4 attributes (What, Where, When and Who)[5]. This idea was important to the development of Terminal 5 at Heathrow. The 'Why' team, which represented the client's interest worked together with the 'How' team to resolve what would be done, by whom when and where. A simplified version of the process is shown in Figure 1 [4].

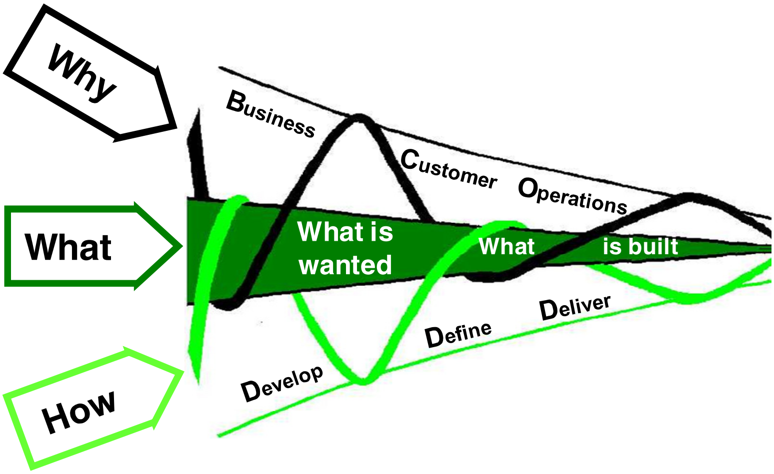

Fig. 1 Design spirals for construction (after T5 Handbook)

2 Dealing with Complex Problem Situations

Kurtz and Snowden [6] Figure 2 provide a knowledge orientated view of complexity which has been found to be particularly helpful because it helps to diagnose the type of process needed to deal with it. It postulates that in a complex state, "cause and effect are only coherent in retrospect and do not repeat", we require pattern management and perspective filters to make sense of the system. The system is managed by a process of 'probe-sense-respond' which implies that the need is to learn our way to understanding the system for its specified purpose rather than just knowing it well enough to be able to make dependable predictions. Each stakeholder has a perspective filter or point of view that will be different from that of other stakeholders.

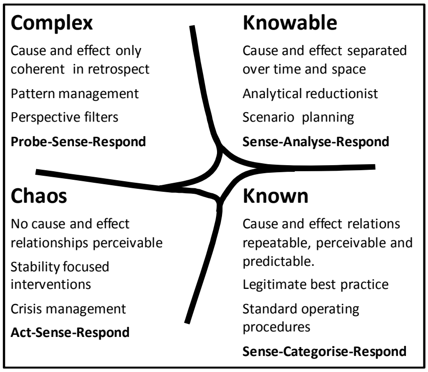

Fig. 2 Sense making in a complex world after [6]

2.1 Emergent Properties

Outcomes from complex systems can be seen as 'emergent properties' of the system. These properties derive from the relationship between the components not just the properties of the components themselves and these relationships are often many to many within the system. Just as the positive aim is to deliver intended outcomes so it will be necessary to manage the unintended emergent behaviours throughout the life of the system. This is particularly important in the commissioning phase of new complex systems. Learning processes need to be included. Unfortunately in many large scale systems there can be no opportunity to build a prototype. It follows that the system has to be designed to have sufficient learning processes within it, combined with resilience and adaptability so that unintended consequences are managed to a successful outcome.

2.2 Core Process for Architecting Complex Systems

By reflecting the work of 300 students and Research Engineers, common themes have been extracted from the more successful and reflected on to industrial experience with the help of Industrial Partners at the Systems Centre, as identified in acknowledgements below. It is apparent that there is a fundamental organising principle underpinning success. At its top level this is shown in Figure 3.

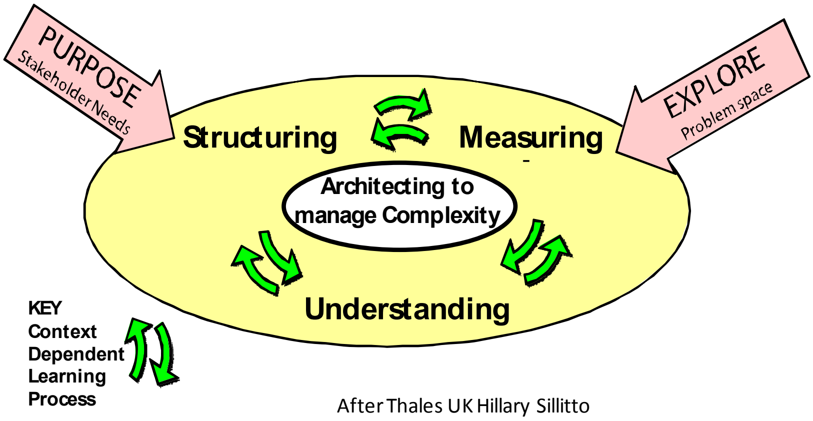

Fig. 3 Architecting process for the design of a complex system

2.3 Frameworks for Structuring and Measuring

The concept of a framework for systems architecture owes its origins to information systems and particularly Zachmann [2] and is seen as *a set of tools which can be used for developing a broad range of different* architectures [7]. As indicated earlier, it is necessary to go back to first principles, when addressing new domains and problems, because if a framework is not suitable to a particular domain it tends to obfuscate rather than clarify. Zachmann's specialisation of the general structure to the information system domain does not seem to be transferable to other domains. Frameworks are used to reduce perceived complexity by separation of concerns hence generating understanding in the face of complexity. Inappropriate frameworks increase the perceived complexity. The goal of the context dependent learning process shown as double arrows in the diagram, is clarity of understanding. This provides a criteria for success for the framework generation process. The double arrows indicate repeated iterations until sufficient clarity is generated. However this requires experience and an ethical judgement that avoids confusing clarity with simplicity.

3 Attributes of a Good Framework

The problem is usually too complex to be dealt with in a single diagram instead as with Zackman a layered approach is recommended. By exposing these relationships, changes can be proposed and evaluated. Frameworks generally need to be multidimensional, representing various important viewpoints on the problem situation. The attributes of a good framework include that the dimensions in any one view should be "MECE" – mutually exclusive, and collectively exhaustive [8]. The dimensional subdivisions should also be of a similar level of importance.

3.1 Stakeholder Needs Defining Purpose

It is clearly necessary to explore the problem space in order to appreciate the context. However a key process is also to identify purpose through an analysis of stakeholder views of the system. This links the framework to purpose ie Why, through the stakeholders who are generally a significant source of complexity. The processes tend to identify particular issues and relationships. There are a wide range of tools for this including: UML Use cases, analysis of roles and responsibilities, importance-influence analysis[3] also grounded theory interviews[9] and story telling [9].

4 Sustainability

Sustainability is a desired attribute of many systems. It is complex and multidimensional. There are many examples of narrow definitions of sustainability leading to decisions being made, that have been at best partially effective and at worst counterproductive when considered holistically. These unintended consequences, resulting from well intentioned decisions have been a motivating force for the sustainable systems research described earlier. For example:

- the decision to insist on the use of bio-fuels in transport, lead to the emergence of food riots caused by change in agricultural and market driven practice [10]
- The un-sustainability of the green energy subsidies [11]
- Forest fire suppression causes greater tree density and fuel accumulation, leading to larger, hotter, and more dangerous fires, often consuming trees that previously survived smaller fires unharmed. [12]
- the emergence of instabilities in the stock market from automatic trading [13]

Sustainability itself has different meanings for people with different points of view. To eliminate this potential for confusion, the sustainable systems team at Bristol shared their understandings and through a process of group model building developed a simple layered structure for Sustainable Systems as shown in Figure 4: Blue and green sustainability.

Green sustainability applies to the Sustainable Development of infrastructure. The Bruntiland Report [14] defines it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". For example wind farms, reed beds and wind up radios may all contribute to “green sustainability”. Blue sustainability refers to systems that are capable of operating long term in conditions that are very challenging because they are isolated, safety critical or extreme. Examples include: space, nuclear reactors and deep sea. Both are seen to be within a meta view that requires the outcome to be efficient, effective, resilient, robust and affordable.

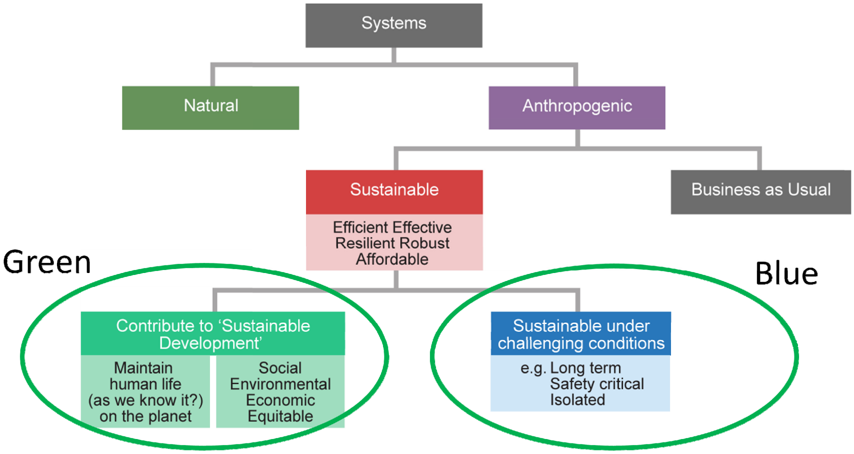

Fig. 4 Blue-green sustainability

4.1 *Holistic Dimensions for Sustainability*

For business there are a range of holistic scales that are used to establish a meta framework for business strategy analysis. PESTLE: Political, Economic, Social, Technical, Legal, Environmental is a commonly used example. This is sometimes extended to STEEPLED to identify additional sub-division of the whole for Ethics and Demographics. One of these can be used for sustainable systems design. The 5 capitals scale [15] Figure 5, being expressed as capitals, recognises that resource is finite and at least conceptually quantifiable. It too can have additional subdivisions. For example, some would distinguish between 'Social' and 'Institutions' because in some contexts institutions are as important as social and human. So, it becomes 6 capitals. For example the Regulator(s) of a system can have a profound and not necessarily beneficial influence on the sustainability of a system.

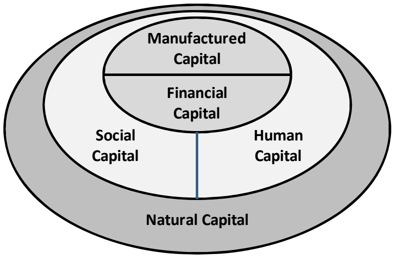

Fig. 5 Five capitals

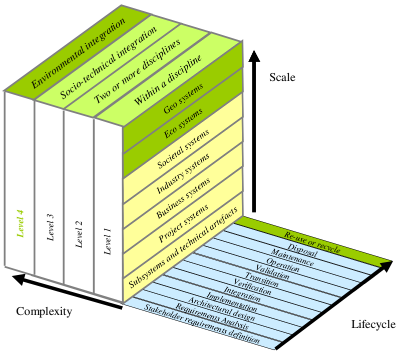

Fig. 6 Extension of standard scales for sustainability

Alternatively standard scales can be extended as is shown in Figure 6 [16] to include for environmental measures. In this case 'lifecycle' is an extension of the scale provided in ISO 15288, 'scale' is an extension of Hitchin's 5 level scale[17].

Complexity is an extension of Supples scale published by Royal Academy of Engineering [18].

5 Using the Framework

Conceptually the layered framework is a problem structuring method that sits between policy or need and a real world context Fig 7. Ideally the framework should be used to test policy before it is enacted as is evident from the examples identified under the sustainability heading.

Because performance depends upon the interaction of the components it is usually necessary to use interpretive models to understand what is going on and predictive models to understand the implication of the interdependencies which can be multidiscipline. Systems Dynamics[19] and concept mapping are useful tools to understand causal loops. Systems Dynamics is extensible to simulation with the inclusion of stock-flows. Agent based modelling is also useful and can be used to feed relationships into the simulation. Sometimes it is useful to use shared model building to engage people who are involved in the process [20].

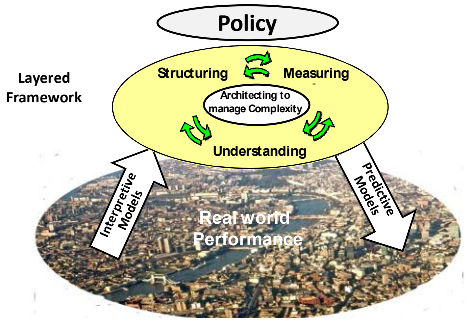

Fig. 7 Developing the Framework to inform policy

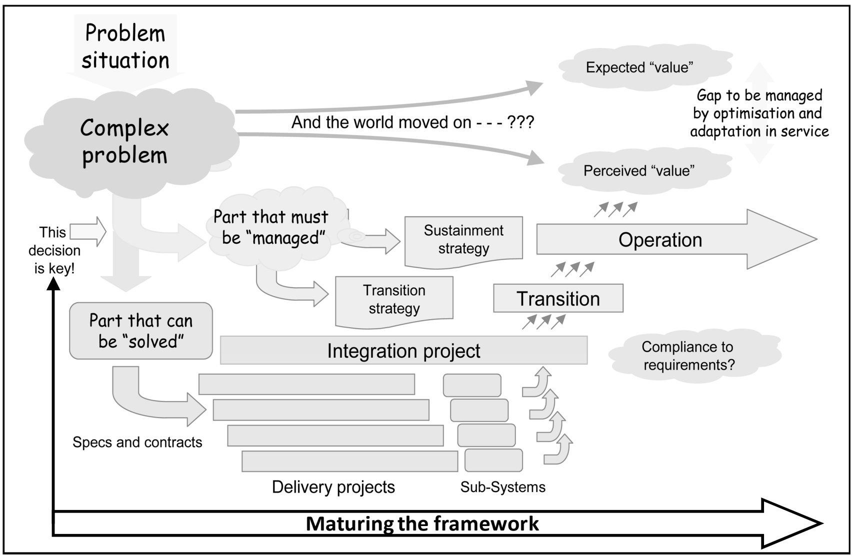

Fig. 8 Complex Systems Engineering after Sillitto [2010]

Figure 8 superimposes the framework development process on Sillitto's model for complex system engineering of ultra large scale systems[21]. The framework needs to be in place to inform the initial key decision as to what part of the problem is engineered and what part is to be managed on an ongoing basis. It is very risky to establish a project before it is in a sufficiently knowable state. The logistic disruption that occurs when an unintended consequence emerges is generally very costly and time consuming. There are traditional processes for this transfer. For example the process of obtaining planning permission resolves a range of social objections to the project which could otherwise delay and disrupt the work. These processes are necessary but not sufficient. For example, the start of the Channel Tunnel Rail Link was contemporary with the Newbery by-pass protests but through effective stakeholder management the vulnerability to protests was avoided.

6 Conclusions

This work has shown the importance of establishing a meta framework and language to deal with the emergent behaviours and unintended consequences that characterise complex systems.

Architectures are intended to generate understanding in the face of complexity that will move the problem into a knowable state at least sufficiently to enable design that will fulfil the systems purpose. Stakeholder needs define purpose but also reveal conflicts that will need to be managed. Once the important relationships have been identified then causal loops can be abstracted and if necessary extended through stock flows to provide simulations of performance. At the top level these can be used to test the economics or policy. At the systems engineering level, it can also provide a base line to monitor emerging knowledge from complexity which will inevitably be the source of uncertainty. It is also used to design and manage a project portfolio approach to project organisation as was the case for the London 2012 Olympics. The learning process is particularly important at the commissioning stage when full integration in service can and normally will reveals unintended consequences. In order to manage the uncertainty it is necessary to have a design that is both resilient and adaptable.

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