The Role of Systems Engineering in Innovation

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Abstract

The discipline of Systems Engineering encompasses both systemic and systematic thinking and, for many organisations, it is fundamental to the realisation of new ideas in products, services, and systems. Maturation of technologies from concept through to operation is sometimes measure through nine Technology Readiness Levels (TRLs), originally defined by NASA. The cost of maturation through the middle levels (5-7) is many times greater than the initial investment (1-4) and is known as the "valley of death", because many new concepts fail, or are abandoned, at these stages. The higher levels (6+) of readiness are characterised by activities of integration, which is the essential contribution of Systems Engineering.

In this presentation, Prof. Henshaw will provide an overview of Systems Engineering and demonstrate its essential role in innovation. He will argue that Systems Engineering should be a skill that is developed in all engineers and that an appreciation of "Systems of Systems" engineering is essential for modern complex systems innovation.

Introduction

The discipline of Systems Engineering is concerned with both the systemic (behaviour of a system as a whole and its interaction with its environment) and the systematic (concerned with the detail of how a system's parts interact and are put together. In this short paper, I shall argue that in general innovation requires consideration of both the systemic and the systematic and that one without the other makes innovation less likely. Consider a highly complex, innovative capability: the F117 (Nighthawk). This was the first stealth aircraft, developed by Lockheed Martin Skunk Works in 1970s/80s. Lockheed analyst Denys Overholser came across a paper by Russian mathematician, Pyotr Ufimtsev[1], concerned with radar detection and realised that he could use this to design an aircraft with very low radar signature. Thus the systemic nature of the F117 is that it is almost undetectable by radar, but the systematic nature is that there are electromagnetics, aerodynamics, structures, propulsion, control, and many more individual challenges that must be overcome with appropriate technologies and integrated together to achieve this capability.

A nail is a highly innovative component (the inventor is not so easily identified), but it provides a means through which structures can be created. In this case, the systematic aspect is the nail (and hammer, of course), but the outcome of using them may be an object that is appreciated systemically and can usually only be planned by conceiving the object holistically *a priori*.

There is a tendency to think of innovation as being synonymous with invention (Bessant 2003), but it is really about taking an idea through to commercial success or societal benefit. It may be radical, but is more usually incremental (Tidd et al. 2005) and may occur at either the component or system level.

Process or Culture?

Some years ago I was asked to write a chapter on the "innovation process" in aeronautics (Henshaw 2012), meaning the procedural nature of innovation. I concluded that, from an organisational perspective, environment and culture were of much more significance than process, noting the view of Steve Jobs. "How do you systemise innovation?" "You don't" replied Steve Jobs, chairman and CEO of Apple Computers (Jobs 2004). "You hire good people who will challenge each other every day to make the best products possible.... ... Our corporate culture is simple." However, I noted that in domains such as aerospace, the future challenges are highly complex and should address not just technology, but legal, social, environmental, financial, etc. aspects as well. Indeed, a (whole) systems approach is needed.

If we set aside the notion of "systematic innovation" meaning a step by step process for innovation, and turn our attention to the process of technology development[2], then the meticulous process of development using

[1] UCI Ufimtsev, Pyotr Ya. "Method of Edge Waves in the Physical Theory of Diffraction." Journal of the Moscow Institute for Radio Engineering, 1964

[2] It is recognised that technology is by no means the only source of innovation, but this article considers only technological innovation.

Systems Engineering could be seen as an enabler of innovation.

Technology Readiness Levels

Technology Readiness Levels (TRLs) were introduced by NASA to track the maturity of technology projects (Mankins 1995); they have become the de facto measure of maturity in many organisations. TRLs range from 1 to 9 (see box) and represent the phases of research and invention (1-3), innovation (4-7), and commercial market (8-9). It is a generally held belief that many projects are terminated in the TRL 4-7 range (European commission 2012), although precise figures are hard to find and it is also not clear what a reasonable level of failure at this level of maturity would be (Héder 2017). The costs associated with development increase substantially in this range, compared to TRL 1-3, and so a proportion of project termination is to be expected. The causes may be manifold, but it is noted that from TRL 6 every level involves integration in some form. If systems engineering has been applied from the outset of the project, then the likelihood of success is increased (Honour 2013), and certainly systems engineering is an essential part of integration.

Technology Readiness Levels Summary

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 4	Component and/or breadboard validation in laboratory experiment
TRL 5	Component and/or breadboard validation in relevant environment
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and "flight qualified" through test and demonstration (ground or space)
TRL 9	Actual system "flight proven" through successful mission operations.

John Mankins, 1995, NASA Report

Qualities of Innovation and of Systems Engineering

One important factor in innovation success is meeting customer or user expectations, and effective requirements management is the cornerstone of good systems engineering. A corollary of this is that technical "inventiveness" at the component level may not translate into innovation success, because usually the customer is concerned with what the system (or device) can do, rather than how it does it. in his excellent book, "The Myths of Innovation", Berkun draws attention to the fact that innovation does not just rely on technical prowess, but also on commercial proficiency (Berkun 2010). He also disagrees with the notion of the Eureka moment, arguing instead that the creative moment is not the sudden emergence of an idea, but rather the fitting of the last piece of a jigsaw that shows the inventor how a change may be achieved. This is very well illustrated by an example that I often give to undergraduate engineers, entitled: "How the Wright Brothers Exemplified Systems Engineering", which I base on the biography of (Jakab 1990)[3]. These are the attributes they displayed:

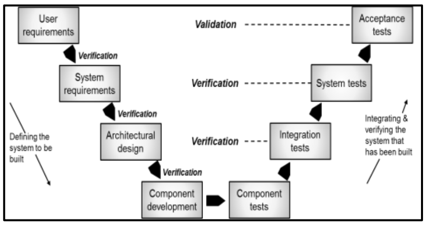
- Conducted literature review: Contacted the Smithsonian and Chanute to assemble all the information they could find, then learned what worked but also what didn't work
- Effective Decision Making: Used a court of family members to resolve disputes. Effective teamwork allows disagreements but always resolved in a positive manner
- Holistic thinking: conceived the aeroplane as a whole system – control/stability, aerodynamics, propulsion, structure
- Understand the problem: they were first to recognise the control/stability problem properly (used a foreplane with different angle of attack to restore stable flight condition rather than relying on human control, as Lielenthal had done)
- Include humans/users in the system: understood the need to learn to fly before attempting the first flight (powered) by practising in gliders
- Knowledge of essential science: knew relevant laws of physics to make appropriate mathematical modelling, e.g. for sizing the vehicle.
- Visual thinking/analysis: they could picture the system in its operation (forces, airflow, etc.) – they could visualise the movement of centre of pressure with a curved surface. Also used a prone pilot to reduce drag
- Synergistic thinking: used bicycle knowledge of balance and user interaction to assist understanding; were also inspired by a cardboard box for understanding wing warping.

[3] Of course, I realise that the Wright Brothers would not have referred to themselves as Systems Engineers, but they were, nonetheless.

- Practical: their understanding of bicycle building enabled them to be good at making machines to appropriate quality.
- Experimentation: through 100s of hours of wind tunnel experiments, they determined the most efficient aerofoil.
- Manufacturability: they built their vehicles in modular parts for easy construction onsite (also appreciating the logistics challenges of moving the vehicle to the test site)
- Prototyping: used kites to understand forces and behaviours.
- Documentation: kept log books and recorded information – though some was recorded afterwards and not all records are clear.
- Critical thinkers: tested the theory for force due to flow; corrected Smeaton coefficient (long believed to be correct at 0.005) and found an accurate value of 0.0033.
- Re-used appropriate data: used Leilenthal's data sheets for aerofoil forces.

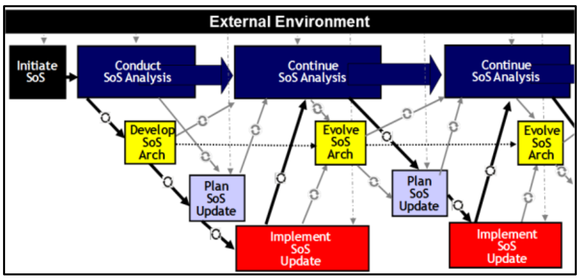
These iconic innovators used both systemic and systematic thinking, which is the quality of good systems engineers.

Systems, Systems of Systems, and Standards



The Systems and Software Lifecycle Standard (ISO/IEC/IEEE 2015) describes 30 processes needed to manage development and operationalisation of a system; the processes of many systems companies are based on this standard. The processes, with associated tools, should ensure good technical governance of system development. The well-known Vee model (see panel, due to (Stevens et al. 1998)) captures the essence of the technical processes, demonstrating that the design is established by breaking down the top level requirements into greater and greater granularity, until the components can be manufactured or bought, then integrating in stages to create the desired systems, checking the competence of design and build at each stage (verification) and that the system meets the customer need (validation). It is important to emphasise that the Vee is a model of a lifecycle, it is not a lifecycle per se; it shows the relationships between activities during systems development.

One might justifiably assert that "surely such tight control must stifle innovation". But in fact, innovation can occur at all stages, the Systems Engineering processes are designed to ensure that the risk of errors and faults is reduced through the development and that the purpose is kept in mind throughout. Effectively this manages the risk through the "valley of death", which is a major need for technological innovation (House of Commons Science and Technology Committee 2013). Many useful systems comprise not a unitary system, but combinations of systems, referred to as "Systems of Systems" (SoS). Brook has defined the general case as "...a system (systemic statement) which results from the coupling of a number of constituent systems at some point in their life cycles (systematic statement)" (Brook 2016), but many of the challenges with such complex SoS arise because of managerial or operational independence of the constituent systems (Maier 1998). Because of the massive increase in connectivity of systems since about 2008, (Dahmann & Henshaw 2016) have suggested that all systems should now be considered to be SoS. System development can now be considered to be the connecting of systems with different lifecycles and a popular model (especially for defence systems) is the wave model (Dahmann et al. 2011), shown in the panel. This model suggests that planned introduction of new systems and retirement of old offer greater opportunities for agile innovations in the overall SoS, whilst maintaining rigorous integration of constituent systems. With many SoS, individual users have the opportunity to create new capabilities by rapidly assembling interoperable systems to meet their needs. This is only possible because of interoperability standards; thus we see that standards far from inhibiting innovation (through constraints), may actually be critical enablers by allowing systems users the flexibility to reconfigure their resources.



Some Concluding Remarks

Ideas are not enough for innovation; one needs ideas and the vision, skills, and perseverance to transform the ideas into real systems or devices. To do this, a systematic process that manages risk effectively is required. It is generally believed that many good project ideas fail (or terminate) as they are developed through TRLs 4-7 (the valley of death), and European governments have asserted that failures in this phase of development means that European nations under-perform in terms of commercial exploitation of ideas (European commission 2012). As technology matures, so integration becomes the main challenge (whether that be integration with other systems or into the environment); Systems Engineering is the discipline concerned with integration and so can be viewed as an essential capability for innovators. Systems Engineering is not generally needed for relatively simple systems and may be viewed as an overhead (e.g. whereas one needs to be systems-minded to build a wristwatch, the full effort of Systems Engineering is not required), it is essential for complex projects (e.g. during development, the highly innovative aircraft Eurofighter had about 4,000 engineers from four different countries working on it).

Although Systems Engineering is needed to manage the risk of integration, it should be noted that a better understanding and more effective tools for risk management are required, and remain a priority research need.

Bessant has asserted that: "successful innovation management is not about doing one thing well, but rather organising and managing a variety of different elements in an integrated and strategically coherent fashion" (Bessant 2003). We would respond by saying that for technical innovation, the organising and managing of different elements can be achieved through application of Systems Engineering. But we would assert that systematic innovation, without systemic thinking throughout the project, is unlikely to yield success. Fortunately, the tools and processes of Systems Engineering, and the skills and training of Systems Engineers, encompasses both systemic and systematic thinking; and so Systems Engineering is the essential discipline for achieving effective innovation.

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