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Engineering Complicated Systems Still Needs Systems Engineering and Thinking

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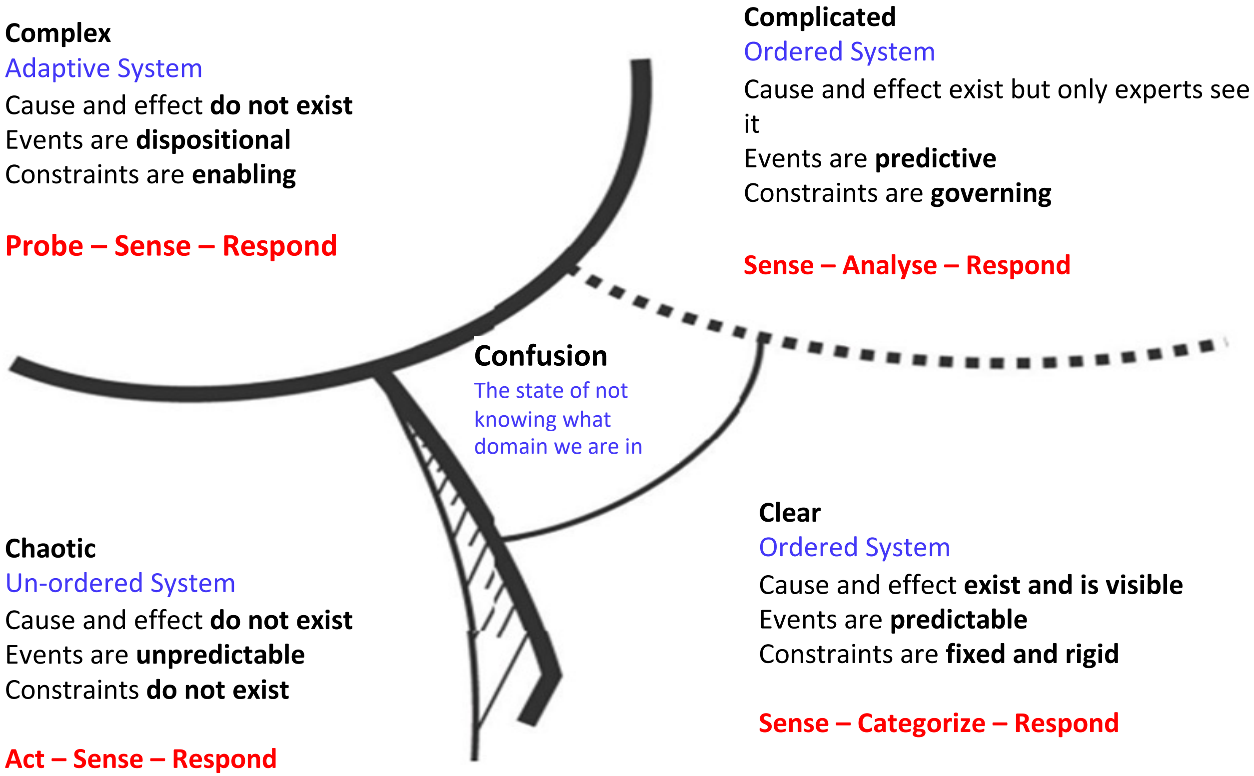
ROLLS ROYCE

Contents and Motivation

- Systems Engineering is intended to increase probability of developing successful systems
- Traditionally, the Systems that Systems Engineers worked on were "complicated" products (with hierarchical structure)
- Increasingly, the importance of considering complex system situations (Systems of systems, Capability systems) is being recognised
- Unfortunately this has led to an idea that "merely" complicated systems do not need Systems Engineering / Systems Thinking
  - One author was told in answer to question about complex systems in paper of importance of Systems Thinking to complex systems that "complicated systems are predictable, and so expecting value from applying Systems Thinking to them is naïve"
- This paper is intended as
  - A reminder that Systems Engineering / Thinking **DO** add value and are essential to engineering complicated systems
  - An illustration of that from experience of application of Systems Engineering / Thinking to (complicated) Gas Turbine power systems

Complex versus Complicated System Situations (1)



- There are different system situations (see Cynefin network)
- These are all systems, but require important differences in approach due to their differences
- Key difference is top down is possible (with iteration) for complicated, whereas not appropriate for complex

See
- Cynefin framework picture from - Snowden, D, 2021, *Managing Complexity (and Chaos) in times of Crisis"*, © European Union, Publication Office of the European Union, ISBN 978-92-76-28843-5
- Different System situation - are different system situations (see Cynefin network)
  - Kemp, D, Beasley, R, and Williams, S, 2015, *Suits you Sir! Choosing the Right Style of SE before Tailoring to Fit,* INCOSE International Symposium 25, 2015, Seattle
  - Quoted in Sillitto, H, Griego, R, Arnold, E, Dori, D, Martin, J, McKinney, D, Godfrey, P, Krob, D, and Jackson, S, 2018, *Envisioning Systems Engineering as a Transdisciplinary Venture,* INCOSE International Symposium 28, Washington DC

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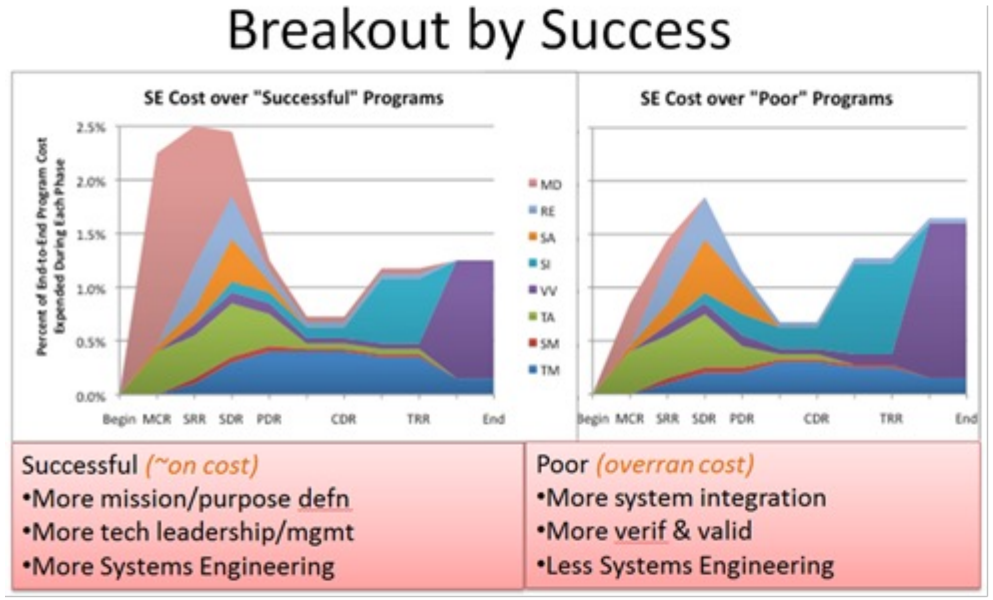
How SE delivers values – Basics

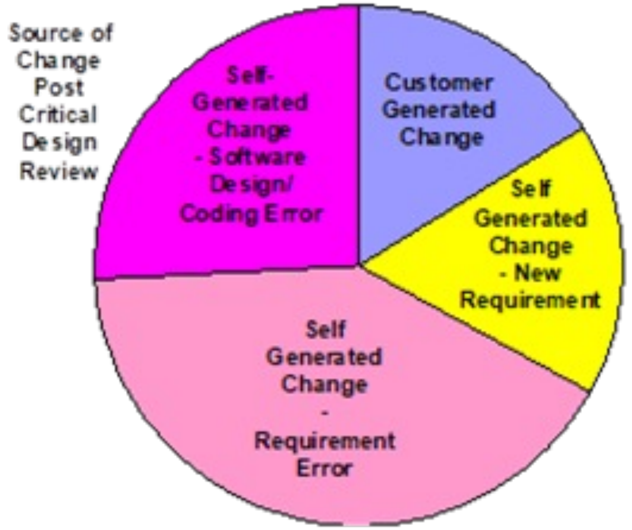


Difference between Successful and Unsuccessful Projects.

MD = Mission/Purpose Definition, RE = Requirements Engineering, SA = Systems Architecting, SI = Systems Integration, VV = Verification & Validation, TA = Technical Analysis, SM = Scope Management, TM = Technical Leadership/Management

From Honour, E, 2013, *Systems Engineering Return on Investment,* PhD thesis, Univ of South Australia, accessed at http://www.honourcode.com/seroi/

Change is inevitable



….and mostly self-generated

From Pickard, A, Nolan, A and Beasley, R, 2010, *Certainty, Risk and Gambling in the Development of Complex Systems*, INCOSE-2010-461, 20th Anniversary INCOSE International Symposium, Chicago, 2010, ISBN 0-9720562-8-9

- Understand purpose / context (from Mission Definition)
- Identify and manage traceability / rationale for solution, to cope with (inevitable) change

Trends in Complex Vs Complicated Systems

Complex?
Complicated?

Complicated?
Complex?

- Systems are becoming increasing more interconnected and entangled, so complex system situations are on the rise
  - Developing Systems practice to address complex systems is a priority
- Complicated systems will still exist (the systems in a system of systems!) and the fundamentals still apply
- In "natural" language complex and complicated are near synonyms, but in Systems Engineering a precision of language is needed
  - A complicated system is ordered, cause and effect exist, but only experts see it.
  - A complex system is an adaptive system and cause and effect are hard / impossible to discern
  - Having lots of parts, or multiple stakeholders with conflicting / inconsistent needs does not make a complicated system complex!

Summary of Rolls-Royce view of benefits of applying SE, and what is needed for success

Benefits of SE (RR experience)

- Avoiding scrap / rework is essential – without effort 50% rates can occur – and late detection more than doubles cost of correction
- Most is generated internally by solution development team (NOT customer changes)
- Systems Engineering and Technical Risk management are crucial (and linked tools) to reducing the rate and impact of change
- The “systems effort” to do this pays back (pre-work avoids later cost) at 100:1

The organisation and people matter (after Long, 2021)

- Need T shaped People (vertical is technical depth, horizontal is communication across disciplines)
- Trusts (in the people creating the models)
- Transparency (question the thought processes)
- Accepting the Vulnerability this can create

What matters

- Pre-work not rework – based on understanding system purpose
- Data (Needs, Requirements, Evidence, Definition and Verification) assurance management
- Communication through layers and elements of system
- Iteration between requirements and solutions, and between layers and system elements
- Recognise that the system that engineers systems (complicated or complex) is complex
- The complicated systems inside a complex system of systems have to work

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Systems Thinking

- There is much discussion about the relation between Systems Thinking and Systems Engineering
- For the authors
  - Systems Thinking is applying the properties seen in "general" systems as a Framework for Curiosity, giving insight and understanding of the situations
  - Systems Engineering is the systematic application of Systems Thinking, applied to the engineering of a system
- (Over) simplifying, the systematic approach will vary between complex and complicated system
  - Probe – Sense – Respond vs Sense – Analyse – Respond
  - Complex system of systems display properties of "systems of systems" in addition to the properties of systems (so we can suggest there is "Systems of Systems Thinking!)

Properties of Systems (as defined in the INCOSE SE handbook)

1. A system exists within a wider "context" or environment.
2. A system is made up of parts that interact with each other and the wider context.
3. A system has system-level properties ("emergent properties") that are properties of the whole system not attributable to individual parts.
4. A system has the following:
   - A life cycle
   - Function
   - Structure (including boundary, set of parts, and relationships / interfaces between the parts)
   - Behaviour
   - Performance characteristics
5. A system both changes and adapts to its environment when it is deployed (inserted into its environment).
6. Systems contain multiple feedback loops with variable time constants, so that cause-and-effect relationships may not be immediately obvious or easy to determine.

The remainder of this presentation will focus on the application of Systems Thinking to complicated systems – predominantly based on the authors experience with Gas Turbines

Emergence – overview

Nature of Emergent Behaviour	Positive	Watch for and EXPLOIT	Design for
Nature of Emergent Behaviour	Negative	Watch out for (don't assume not there)	Minimise
		No	Yes
		Expected/anticipated?	

- Emergence is not always unexpected / unwanted
- Emergence is the properties of the whole, not just the sum of the parts

Examples of emergence in complicated systems (1) – Gas Turbines

- For Gas Turbines
  - Thrust is expected / desirable property
  - Noise / emissions are expected / undesirable properties

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Examples of emergence in complicated systems (2) – Wobbly Bridges

- Forced mechanical resonance in bridges is a well-known phenomena (Tacoma Narrows “Galloping Gertie” in 1940
- London Millennium footbridge (2000) showed a new emergence:
  - Natural human reaction to small lateral movement in bridge
  - Pedestrians adapted walk to bridge motion (“rolling seaman’s gait”)
  - Essential this changed the natural frequencies of the bridge (as it became moving bridge plus pedestrians)
  - At critical numbers of people, this created instability, as the bridge’s natural ability to absorb motion was removed

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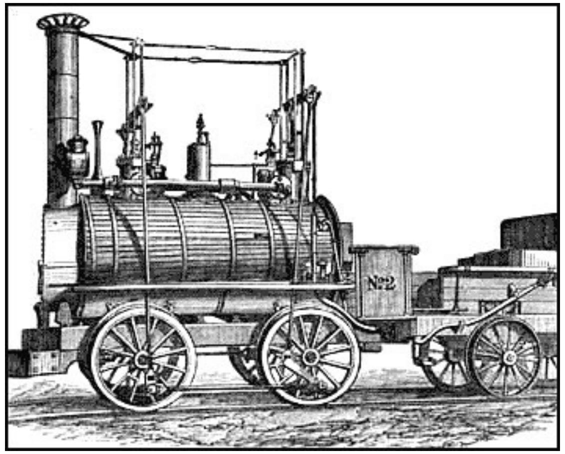
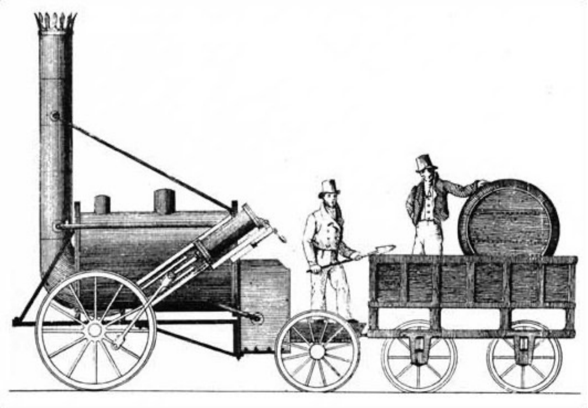
Examples of emergence in complicated systems (3) – Steam Trains

George Stephenson, 1778 - 1848



Blucher engine – designed and built by George Stephenson 1814



- Main problem was insufficient power in engine to drive weight of locomotive
- Additional problem with escaping steam
- Flowing escaping steam through furnace to escape from chimney **DOUBLED POWER OF ENGINE**

- Blucher innovations lead to high performance of the Rocket **in 1829**, and without steam blast, and locomotives would still be dragging themselves along at 5 or 6 miles an hour (written 1874)
- Performance principles of the combustion aerodynamics theoretically understood at Purdue University **in 1908**

- Sources – Samuel Smiles on "the lives of the Engineers", and for theoretical understanding (Purdue) Wikipedia article of George Stephenson

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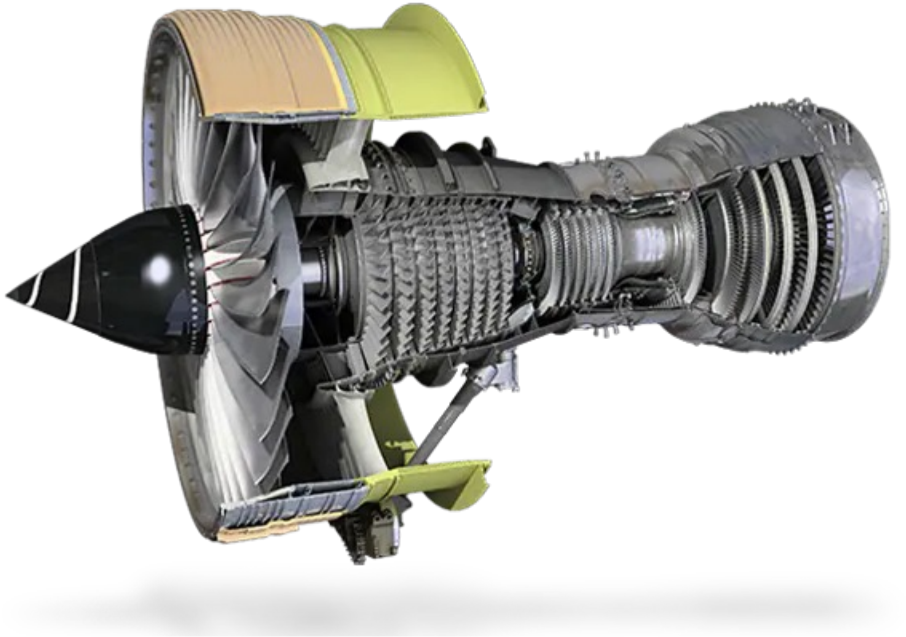
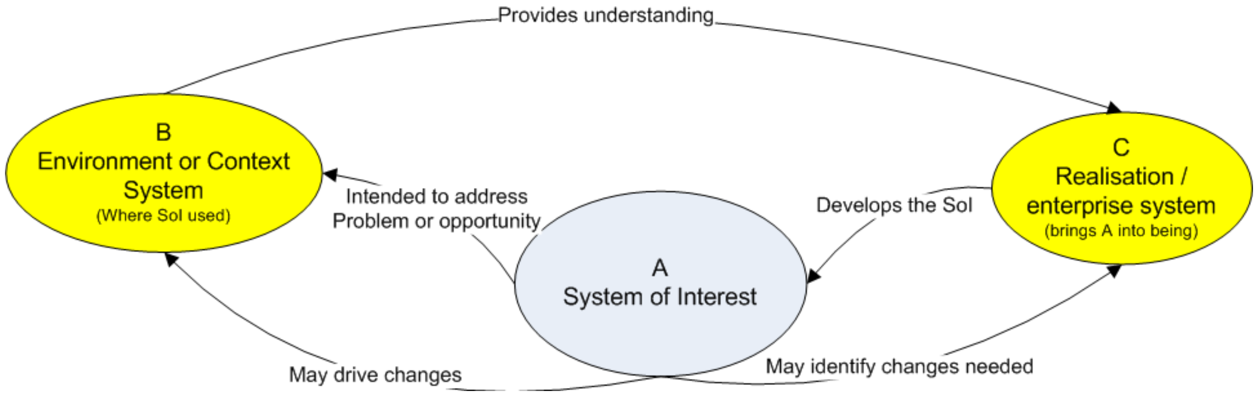
Sub-optimisation – a bad thing that is (too) natural

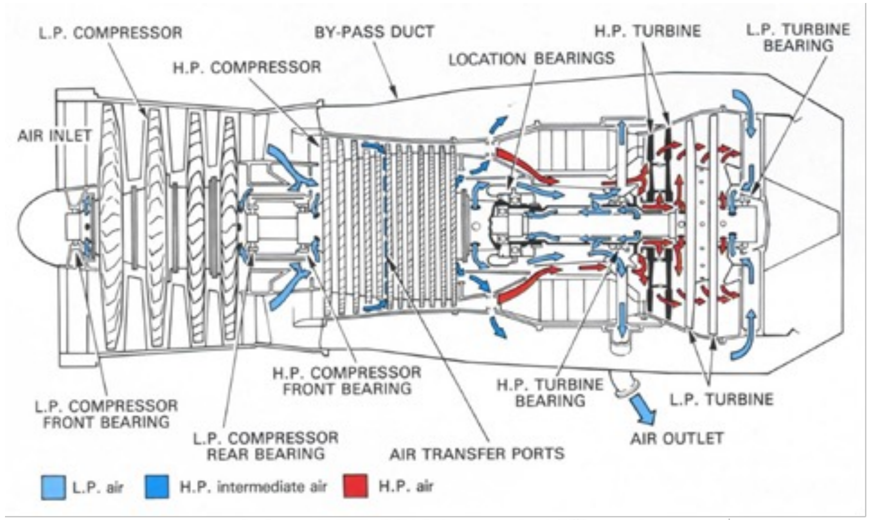
- Gas Turbines have
  - Physical sub-system modules
  - Integrating product systems
  - Components
- Challenge is to "make the pieces to work together to achieve the purpose of the whole", and not sub-optimise any sub-system or part
- However Sub-optimisation is all too common
  - System to create engines is a complex one
  - Human nature for a team to look inward, make things as simple as possible, and form silos
- Systems Thinking (assisting by integrating MBSE) helps ensure common understanding and focus on the whole
- Latest RR Civil engine concept (UltraFan™) attempts to let fan and turbine run at optimal speeds – by adding a gearbox

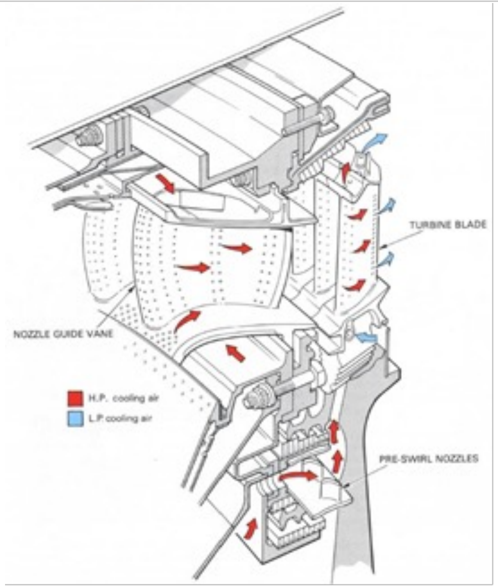




Coupling in Complicated systems

- General Systems Architecture guidance advise against "coupling" the sub-systems
- RR Gas turbines, in order to perform, have lots
- Notably the secondary air system
  - Prime purpose is to balance cycle demands for high temperature with material and component life constraints
  - Secondary purposes
    - Bearing chamber sealing
    - Control hot gas flow in cavities
    - Balance bearing axial loads
    - Blade tip clearance control
    - Engine Anti-icing
    - Air for Aircraft services
- Secondary air system interfaces with most of the physical sub-systems
- Many strong sensitivities to small variations in flow.
- Much engine testing focused on calibrating secondary air system models



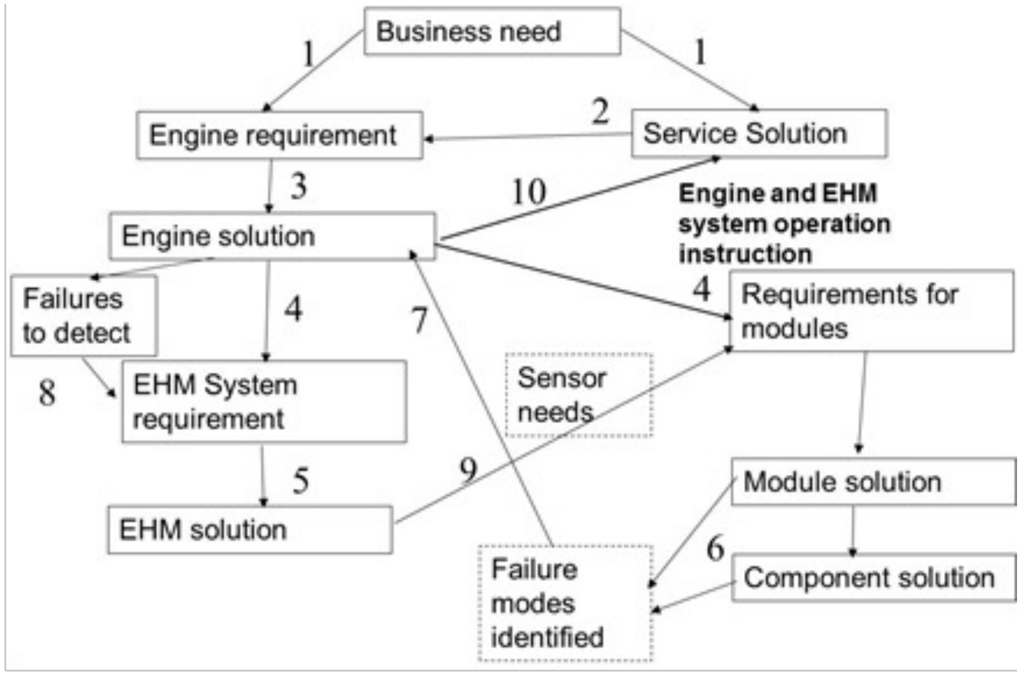


Lifecycle considerations – Health Monitoring

RR gas turbines need to be designed for service / support

Consider an Engine Health Monitoring system

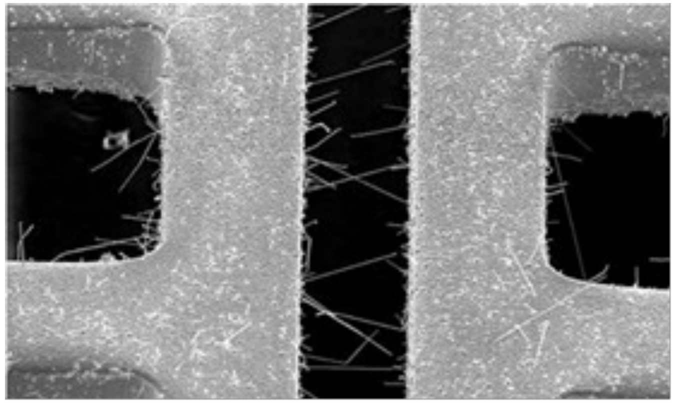
1. Business need for product and service
2. Service profitability needs drive need for "Ilities"
3. Power needs drive engine architecture
4. Whole engine solution decomposed to the sub-system
5. EHM solution developed for service, but recognising engine constrains
6. Detail design identifies failure modes, affecting service cost
7. Consider impact of failures at "service level"
8. Impact of failure drives priorities for EHM system (what it has to detect)
9. EHM drives sensor requirements on components
10. EHM part of solution transferred into service operation



Iterations between levels and systems – but all in a "complicated" system – but depends on Systems Engineering approach

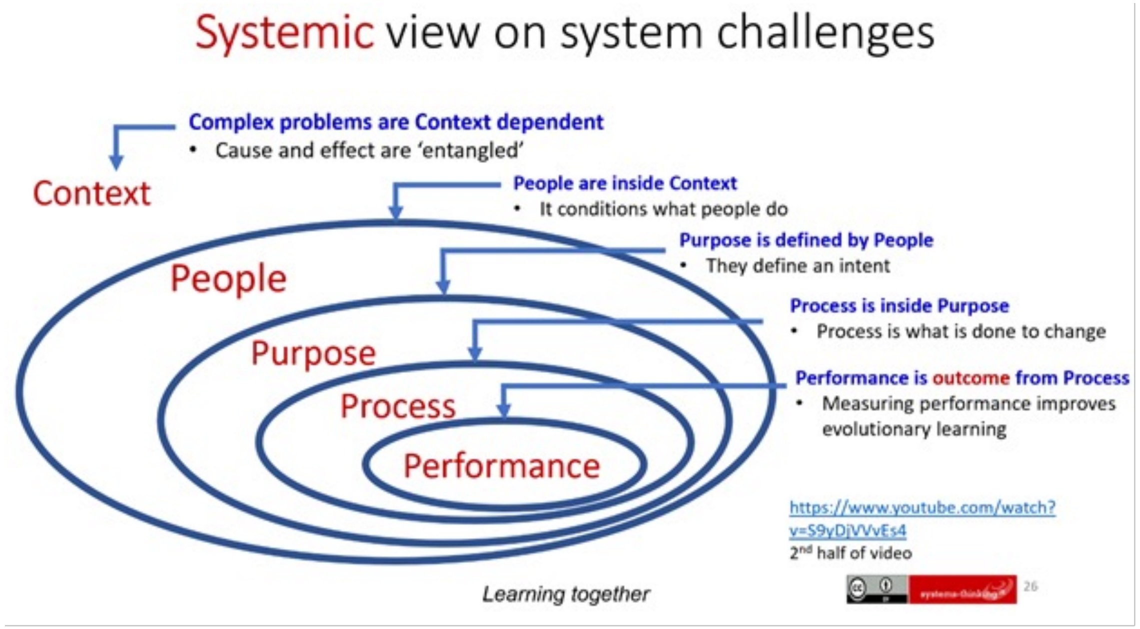
Predictability (often retrospective)

- Predictability wanted but not always possible
  - Use of Lead-free solder leads to “tin whisker” production, and unpredictable (and potentially unsafe) failures in electronic control systems
- Theoretically Gas turbines are predictable, but the highly coupled nature of architecture makes calculations time consuming and difficult
- Modelling joints and interfaces in mechanical structures is a complicated problem, and is limited by our ability to predict the dynamics of the assemblies
  - Many factors (interface geometry, materials contact loads etc.) exists, which have (theoretically predictable) non-linear dependencies
  - Hence the need for significant testing



System Challenges

- Good solutions result from Integrated Product Teams learning together (opposite of the sub-optimisation)
- Apply diverse views of problem to achieve common understanding of purpose
- Organizations are complex adaptive systems – but many principles are the same as complicated systems – but there are obvious differences



Systemic View on System Challenges (Godfrey, 2018)
Using Systems Thinking to address complex engineering challenges", SSSE SWISSED 18

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Conclusions

- Need to keep to basics of how Systems Engineering works
- Basic principles apply to all types of systems
- SE adds value by
  - understanding problems
  - recognizing connections between system and environment
  - Define / maintain linkages between system elements (to focus on purpose of whole)
- All complicated systems are not equal
  - High coupling pushed these complicated systems towards complex
  - High coupling makes predictability much harder
- For us in RR, the only “true” complex system we deal with is the organization / capability to engineer systems

COMPLICATED SYSTEMS NEED SYSTEMS ENGINEERING

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