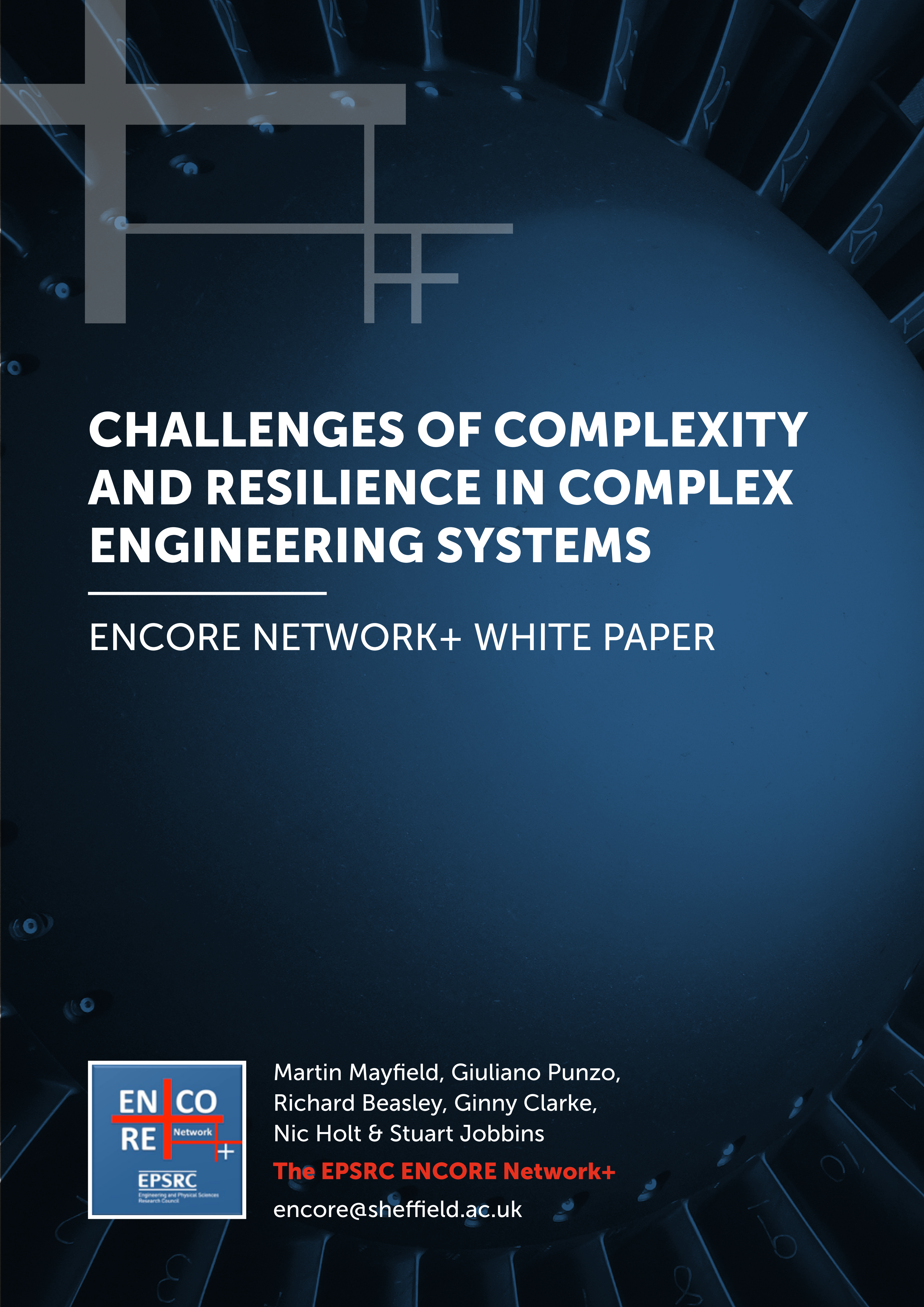


CHALLENGES OF COMPLEXITY AND RESILIENCE IN COMPLEX ENGINEERING SYSTEMS

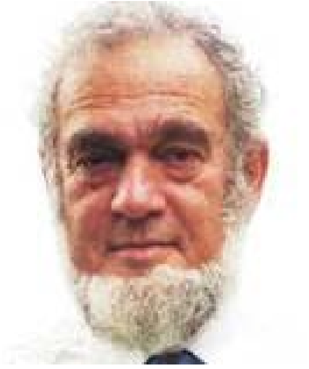
ENCORE NETWORK+ WHITE PAPER

Martin Mayfield, Giuliano Punzo,
Richard Beasley, Ginny Clarke,
Nic Holt & Stuart Jobbins

The EPSRC ENCORE Network+

encore@sheffield.ac.uk

AUTHOR BIOGRAPHIES



Nic Holt

Nic entered the IT industry in 1968 in which he continued throughout a varied career, during which he has gained expertise in a wide range of IT fields, including hardware design and architecture, software engineering, business and technical architecture. In his role as an Enterprise Architect, Nic was responsible for devising coherent solutions that balance the vision and aspirations for clients' businesses with the "art of the possible" – technical feasibility, cost, timescales, risk and flexibility – whilst recognising organisational, human and cultural aspects, often critical to success.

An outstanding innovator, Nic is a named inventor of 11 patents. He has participated in numerous collaborative research projects between industry and academia, notably in novel architectures and parallel processing. He has been active in promoting new programs to support emerging areas of research, most recently in complexity theory. He has served as a Visiting Professor at both Glasgow and Manchester Universities.

Nic is a Fellow of the Royal Academy of Engineering, a Chartered Engineer and Fellow of the British Computer Society.

Stuart Jobbins

MSc CEng FIET MIEEE MINCOSE – Sofintsys Ltd

Stuart has over 35 years experience in engineering of electronic systems, strategic, programme and technical management. His experience covers industrial, defence, automotive, aerospace, marine, nuclear and life-science backgrounds. He has held senior roles in highly respected international businesses, but now heads a consultancy business in Systems and Software Engineering.

Adept at assessing technology, opportunity and risk in the confluence of ideas, adapting and applying the best practices across industries, defining novel features in the use of information for benefit, or in applying technology creatively; he is an acknowledged expert in the definition, leadership and practical application of engineering, having delivered systems that have an enviable reputation for their commercial success, feature set, dependability, safety and time to market.

His most frequent roles are to influence the engineering strategy, both product and process; improve education amongst the engineering competence; identify and lead strategic research and technology development for business benefit.

Stuart sees the engineering challenges of increasing system scale and complexity, dispersed development, coupled with an increased public dependence; yet increasingly about partial replacement in more interconnected, adaptive, mixed-integrity systems, whose design detail may be unavailable.

Stuart is a Visiting Professor in Computer Science and Embedded Systems and sits on a number of national and international Academic and Industrial Advisory Boards.

Ginny Clarke

Ginny has had a varied career in the roads sector, starting her career in local government in the West Midlands on a variety of road transport projects, including the construction of the MAGLEV passenger transit system at Birmingham Airport in the 1980's. She moved to the Department of Transport to take up a role as a bridge engineer, developing and advising on standards for road bridges and then subsequently worked in roles in network planning, project management and technical standards/advice. She became Chief Highway Engineer in 2001 and was responsible for road standards, safety and research on the strategic road network and was the UK's First Delegate at the World Roads Association for six years. Ginny was on the Executive Board of Highways Agency/Highways England for 15 years and took the lead in developing the first Road Investment Strategy and legislation for the new Highways England company in her role as Strategy Director.

Ginny now sits on the Board of Trustees of the Chartered Institution of Highways and Transportation and is chair of the Learned Society and Technical Strategy Board. She is also a trustee of the Rees Jeffreys Road Fund. She was awarded a CBE in 2006 and became a member of the Royal Academy of Engineering in 2011.

Richard Beasley

Richard Beasley joined Rolls-Royce in 1986 with a Physics Degree from Bristol University, and an MSc in Gas Turbine Engineering from Cranfield University. After working on Integration Aerodynamics, Stealth technology, Safety, Reliability and Life Cycle Engineering, he became the Global Chief of Systems Engineering and in 2011 was made a Rolls-Royce Associate Fellow in Systems Engineering. In these last two roles he has focused on integrating Systems Engineering explicitly into the way Rolls-Royce does engineering.

He is an active member of INCOSE (International Council on Systems Engineering, and is the Immediate Past-President of the UK INCOSE Chapter.. He is a Chartered Engineer, Fellow of the Royal Aeronautical Society, INCOSE Expert Systems Engineering Professional (ESEP), and a Visiting Fellow to the Systems Centre at Bristol University.

Professor Martin Mayfield

Professor Martin Mayfield holds the Chair of Engineering Design at the University of Sheffield after 25 years in practice. As a Director of Ove Arup and Partners Ltd, he held a portfolio including Sustainable Building Leader for the UK, Middle East and Africa, Education Leader for the UK, Middle East and Africa and Leader of the Arup office in Sheffield, leading a team of professional Engineers, working on a diverse array of projects in the UK and overseas. Within this team, he led a Built Environment Research Group, providing thought leadership to the wider group and Arup on the future of sustainable design, identifying and driving the research strategy, horizon scanning and leading the technical progression of sustainable building design and research.

His track record, spanning design and research is focused on the pursuit of sustainable design solutions that balances complex engineered systems with natural systems. Martin is the Principle Investigator for the EPSRC ENCORE Network+

Dr Giuliano Punzo

Dr Giuliano Punzo's background is in the broad area of control theory and complex systems. After a degree in aerospace engineering, he briefly joined industry, before his PhD in swarm engineering. Giuliano moved from few vehicles in formation to several autonomous agents and the field of swarm engineering. Later he expanded his interests to robotics, control theory, consensus and complexity. Giuliano is Research Associate at the University of Sheffield and his current commitment is with the EPSRC ENCORE Network+. Giuliano's current research interests include complex dynamical systems, transportation networks, socio-technical systems and their resilience, and a focus on the resources and infrastructure problems in the developing world.

ABSTRACT

The Complex Engineered System domains being explored by ENCORE are Aerospace, Infrastructure, Cities, Communications & Data Networks, and Energy Systems. This paper addresses the challenges of resilience in these domains. It has been written by a group of experts with industrial background together with academics in the ENCORE network.

The paper first argues the need for a common understanding of complex systems in an engineering context and of what makes resilience such a central topic in these systems. For both, definitions are provided. The paper then concentrates on the challenges and opportunities for the research in the field listing and expanding around four main challenges, namely: System Evolution, Increasing Complexity, Design for Resilience and Resilience-Performance Tensioning.

To this, an additional challenge is identified in the training for practitioners, operators and policy makers that, if overlooked, may invalidate any research contribution to the field. Finally, a strategic research agenda is outlined by prioritising the challenges: this is the most important contribution of this paper as it paves the way for the full roadmap for the research field of resilience of complex engineered systems. The full roadmap will be tackled as the next target by the same writing group.

G Punzo, M Mayfield, R Beasley, G Clarke, N Holt, S Jobbins
ENCORE Challenge Paper Writing Group

May 2018

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EXECUTIVE SUMMARY

This paper is the third in a series of papers produced by the ENCORE project, setting out the challenges for the research community in applying theoretical insights from complexity science to improve the resilience of complex engineered systems. The paper has been prepared by a group of professionals with a variety of industry experience and the wider membership of the ENCORE network community.

The importance of understanding and identifying what is a complex system has been examined and the distinctions between complex engineering and engineered systems have been explored. This, aligned with a better understanding of resilience in complex engineered systems, has enabled the authors to identify that methodologies of complexity science need to be specifically developed for the system that is being investigated/designed. A holistic approach to considering the resilience and complexity of a system is crucial to developing understanding across the various domains of complex engineered systems.

Resilience is defined in this paper as the ability of a system to prepare for, mitigate, adapt to, and/or rapidly recover from the effects of endogenous and exogenous “disruptive” events. This definition bridges the literature with the specific characteristics of the complex systems in the ENCORE realm. Characteristics enabling resilient complex systems are identified as those of self-learning and system awareness, drawn from the field of complexity science.

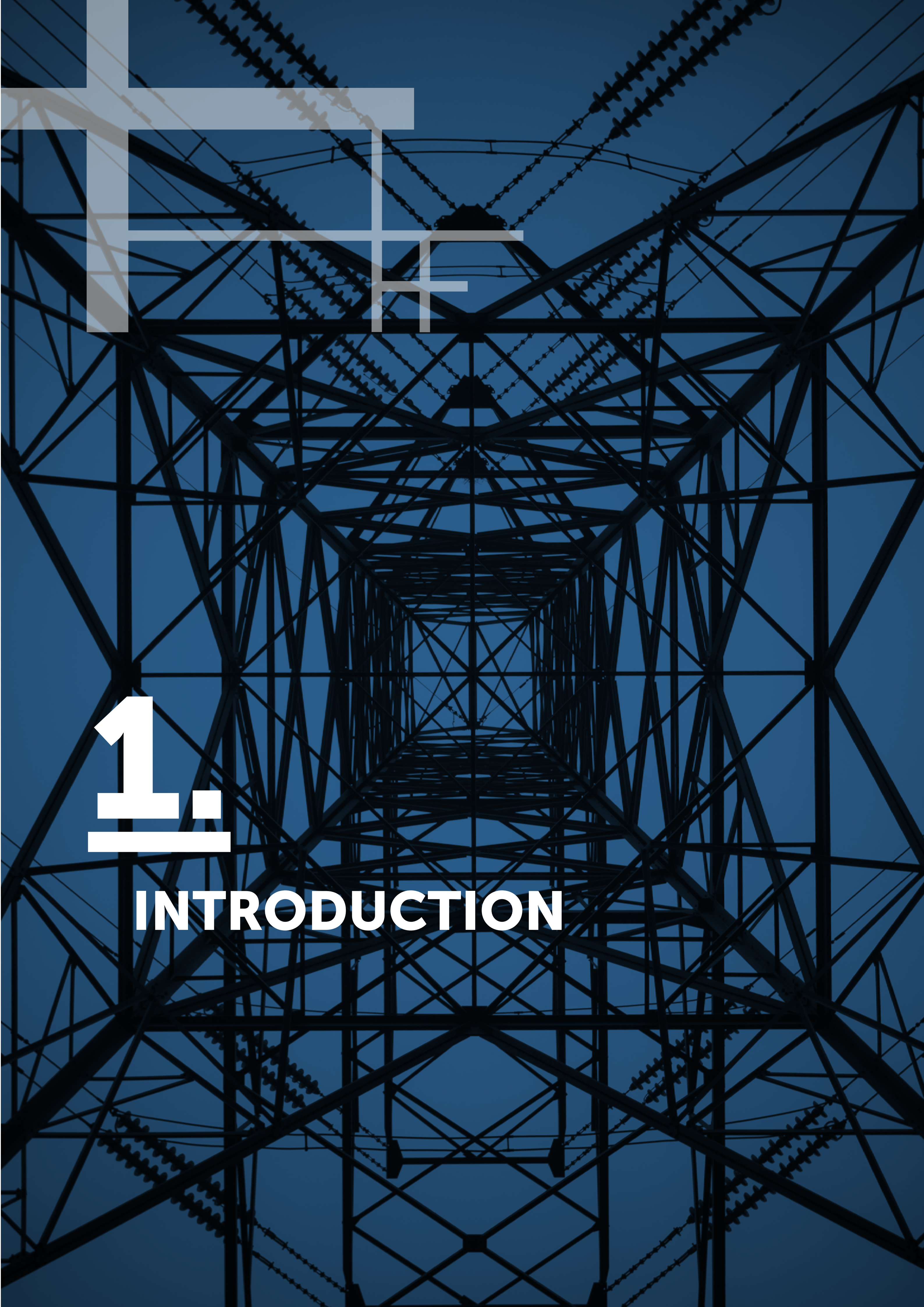
Four key areas of challenge for future research have been proposed by the ENCORE project, namely: 1. System Evolution, 2. Increasing Complexity, 3. Design for Resilience and 4. Resilience-Performance Tensioning, enabling definition of a structure for future research. Based on this structure, the group has identified priorities for research by comparing the influences and impacts of the challenges that could improve the design, planning, evolution and operation of complex systems.

A review of how the science of complexity can be utilised in achieving engineering know-how has highlighted the importance of those in science and engineering working together to share knowledge and produce relevant guidance and methodologies in a world that is changing rapidly. The complexity of systems with greater uncertainties, including those affected by culture, values and expectations of society, have created a wider landscape for engineers. These changes mean that, in addition to the growth needed in the network of complexity scientists, education and training of engineers needs to be updated to enable them to effectively contribute to dealing with complex systems.

Although the focus of the work supporting this paper has been to identify the basis for a road map for future research, the need for action beyond the immediate groupings of researchers and funders has been highlighted. The views on who is involved and the assessment of where action needs to take place, are important in building a picture of the complexity of the environment in which future research will take place. Without an understanding of the wider context and the positive involvement of the various groupings, the impact of further research will be limited.

The roadmap for prioritising future research is not just the product of challenge groupings and preliminary views on research. It comes from thinking and understanding the interfaces of complexity science and engineering. The roadmap highlights the need for fundamental understanding of the systems and increasingly complex society to enable the final target of designing for resilience.

Yet the threat to success in addressing our challenges is in the persistence of inadequate engineering training. This materialises the risk to frustrate any positive advancements of future research in complex systems for engineering. Beside the issue of creating a knowledge transfer channel, the two way engagement with practitioners, operators and policy makers is still to be addressed.



1.

INTRODUCTION

ENCORE is an EPSRC Network+ the purpose of which is to connect the communities of researchers and practitioners in Complexity, Engineering and Resilience to define the direction of academic research in order to contribute to the industrial development of Complex Engineering Systems. The activity of the network, so far, has brought together these communities by organising workshops, funding feasibility studies at the intersection of Resilience, Engineering and Complexity and promoting the collaborations aimed at producing new knowledge in this area.

This paper is the third, after the position and methods review papers [Punzo et al., Under review, Tewari et al. In preparation] produced by the ENCORE Network+. It delivers a picture of the challenges to which the research community is required to respond. These challenges have been set by a cohort of professionals from the UK industrial sector, who authored this paper with contributions from the wider ENCORE network community.

Objectives of the Paper

This paper is the third of a series of four documents produced by the ENCORE community.

P1 - Position Paper

The position paper explores the intersection between resilience and complex engineering systems, scoping the field in this intersection and organising the output according to the ENCORE domains.

P2 - Methods Paper

Within the field identified by P1, P2 considers techniques that have been used in the design and analysis of complex systems and their resilience. It expands the field outside the network domains to capture important methods from these. P2 is based on the outcome of the events and workshops, interviews with network members, the outcome of the feasibility studies and any research output provided by the network.

P3 - Challenge White Paper (this paper)

Within the field identified by P1, P3 explores challenges in engineering resilience that might be addressed by Complexity Science and, in particular, through the methods identified in P2. This again will be shaped based on the interactions within the network (workshops, events, interviews, Feasibility Studies).

Our society is increasingly reliant upon engineered systems of unprecedented and growing complexity.

P4 - Strategic Research Agenda

This will be constructed on the basis of the previous three papers. In particular it seeks to answer the following questions:

- WHY is complexity science important in relation to resilience? (Framework - P1)
- HOW are we going to address this? (Methods - P2)
- WHAT benefits shall we get out? (Challenges - P3)

These papers seek to deliver, review, critical deconstruct, critique, rebuild and expand on the original ENCORE Grand Challenge statement:

1. *How can we establish the critical elements that define and constrain the performance of CES such as Cities, National Infrastructure and Energy Systems in a manner that will allow our society to thrive within the carrying capacity of the planet and to do so before 2050?*
2. *How can we extend the functional lifetime of mature infrastructure systems through developing our ability to predictively identify mission critical components and patterns of demand, to manage the uncertainty arising from increasing complexity, in a manner that does not increase the current levels of risk to society?*
3. *How can we best ensure that the design and deployment of increasingly complex engineered systems do not suffer from a concomitant increase in fragility?*

This paper will provide a structure for the research challenges, which are fully developed in Section 4, ensuring we a) critically define challenges across and within domains; and b) deliver this in a manner that is legible across our stakeholder groups which is grounded with industrial perspectives.

A Society increasingly reliant on Complex Systems

Our society is increasingly reliant upon engineered systems of unprecedented and growing complexity. These Complex Engineered Systems (CEdS) are the product of the processes developing them within Complex Engineering Systems (CEgS), as will be made clear in this paper. As our manufacturing, service industries, and the products that they deliver, continue to complexify and interact, and we continue to extend and integrate our physical and digital infrastructure, we are becoming increasingly vulnerable to the cascading and escalating effects of failure in highly complex and evolving systems of systems. Consequently, it is becoming increasingly critical that we are able to understand and manage the risk and uncertainty in Complex Engineering and Engineered Systems (CES), through fields such as uncertainty quantification and optimisation under uncertainty that can provide resilient and optimal design and control solutions.

> *These Complex Engineered Systems (CEdS) are the product of the processes developing them within Complex Engineering Systems (CEgS).*

Research on natural complex systems is helping us to understand the implications of inter-dependencies within and between complex adaptive systems. However, unlike natural ecosystems, man-made systems are not designed to evolve through selection and reproduction of successful examples at the expenses of unsuccessful ones, which latter are (by far) the majority.

A Fundamental Lack of Understanding

Understanding CES behaviour is not only important for their theoretical description but has practical industrial implications. Our challenge is two-fold: we lack 1) a coherent understanding of what unifies the complexity of engineered systems such as aerospace systems, cities and our national infrastructure when integrated in their environments, and 2) a firm understanding of the tools, processes and organisations necessary to manage and build CEdS that exhibit resilience or quantify the risks inherent in such systems.

If we are to deal with the challenges presented by CES we will need to exploit and synthesise our current understanding of natural and engineered systems, our current theories of complexity more generally, the quantification and management of uncertainty, the impact of stochastic processes and the use of advanced optimisation techniques. This will lead to the development of powerful new tools and new understanding to enable our Complex Engineering Systems to create resilient Complex Engineered Systems

> *We are becoming increasingly vulnerable to the cascading and escalating effects of failure in highly complex and evolving systems of systems.*

The Infrastructure Trilemma

As an example of the issues we seek to investigate, consider three of our initial domains of focus: cities, national infrastructure and energy systems. These three CES are facing an infrastructure 'trilemma' that may be summarised as:

- **Infrastructure loading is evolving in distribution and increasing** due to urbanisation and population growth, thus increasing the diversity of density and the density of diversity of infrastructure demands.
- Stretched by the growing ratio of peak to base demand, **the socio-technical complexity increases** as a function of the number and types of nodes (where nodes can be any agent or asset) in each sub-system and the number and types of connections between nodes and systems, each reflecting dependencies or interdependencies.
- **The reserve capacity of society to invest in infrastructures is reducing** relative to the rate of increase in size and complexity of the functions that they need to support.

Driving the infrastructure trilemma and remaining bound within it, humanity is creating complex systems that are not understood, nor are affordable for society if they are subjected to the anticipated increases in the frequency and severity of natural and possibly man made shocks and stresses.

We are creating new engineered systems and digitally retrofitting existing ones (cities, energy systems and national infrastructure) as we strive to create prosperity whilst endeavouring to work within the carrying capacity of the planet. Yet the common understanding and tools we use to understand such systems tends to be reductionist when seeking to understand systemic behaviour and a focus on risk in CEdS, rather than developing our understanding of the inherent uncertainties created from systems with high-dimensional functionality driven by multiple layers of emergent characteristics working across many subsystems.

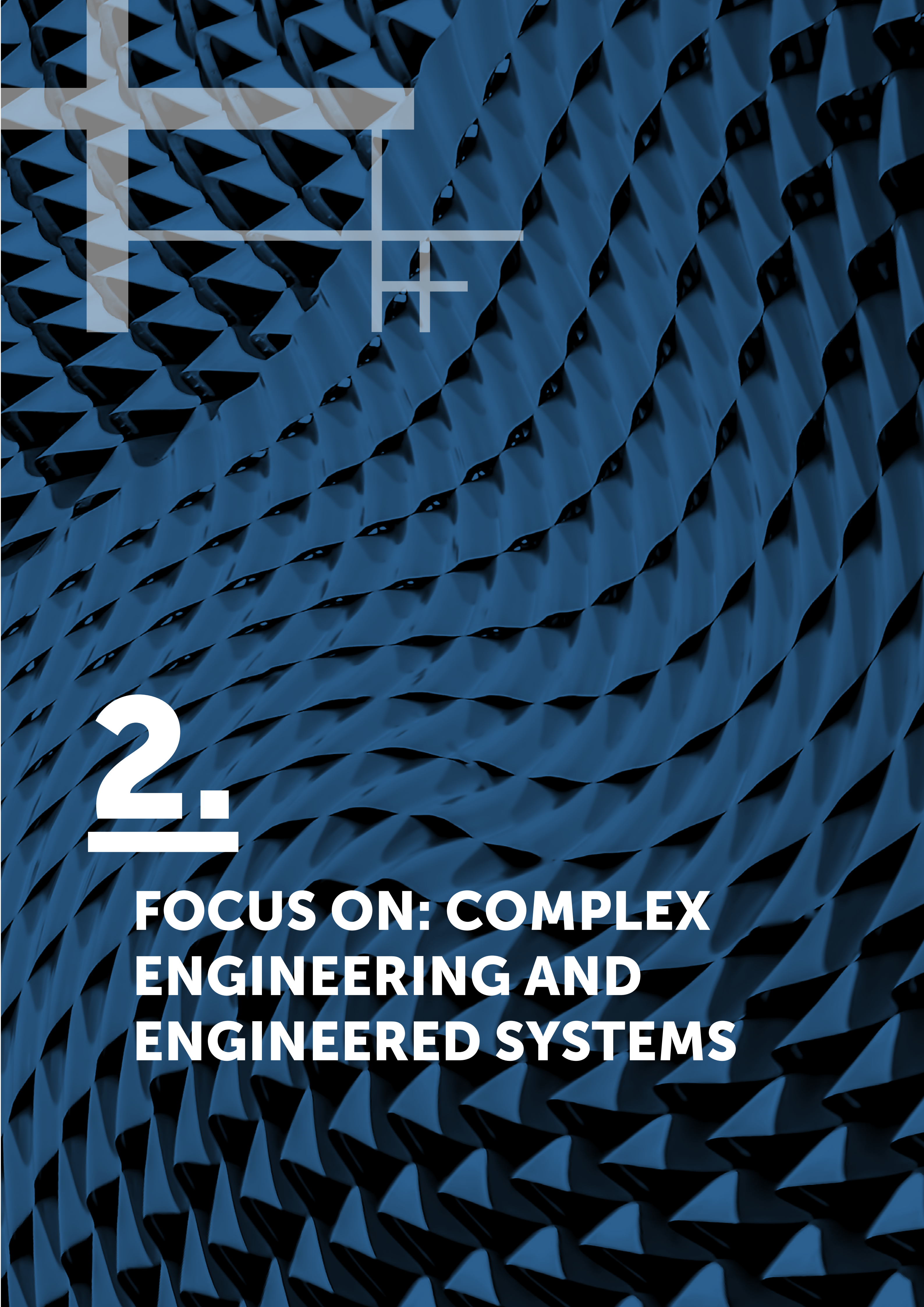
> *It is becoming increasingly critical that we are able to understand and manage the risk and uncertainty in Complex Engineering and Engineered Systems (CES).*

Identifying the Challenges

This paper will explore the current, emerging and potential challenges relating to the resilience of Complex Engineered Systems that might be addressed or progressed by the use of techniques of complexity science.

Writing this paper has taken the joint effort of professionals from industry and academics in the ENCORE Network+ whose combined expertise is leveraged upon the UK's international leadership in the understanding of Complex Systems and in the design and optimisation of CES, the high technological content of its industry and the excellence of its academia.

No immediate solution to the vulnerabilities of our increasingly complex and technological society is achievable without progressing our understanding of CES. Hence, rather than concentrating on offering one, this paper is intended to be a manifesto for research that should be supported by industry/government/regulators. As such, its conclusions are provided through an outline of the strategic research agenda that can deliver the step change needed in the resilience of complex engineering and engineered systems.



2.

FOCUS ON: COMPLEX ENGINEERING AND ENGINEERED SYSTEMS

Complex, Complicated, Engineering and Engineered Systems?

There is a subtle, yet fundamental difference between complex engineer-ing and engineer-ed systems. Referring to the glossary in appendix 1 for more rigorous definitions, here we can simply state that engineering refers to the set of processes and resources that deliver a technical solution, while engineered refers to the outcome of the engineering activity as an assembly of components with certain characteristics.

An engineered system is created with a specific purpose in mind and deliberately engineered to fulfil that purpose. As discussed in detail below, Complex Systems are not fully predictable. Therefore, the engineering of Complex Systems must take full account of complexity, in order to produce systems that can be trusted by society, which is increasingly dependent on such systems.

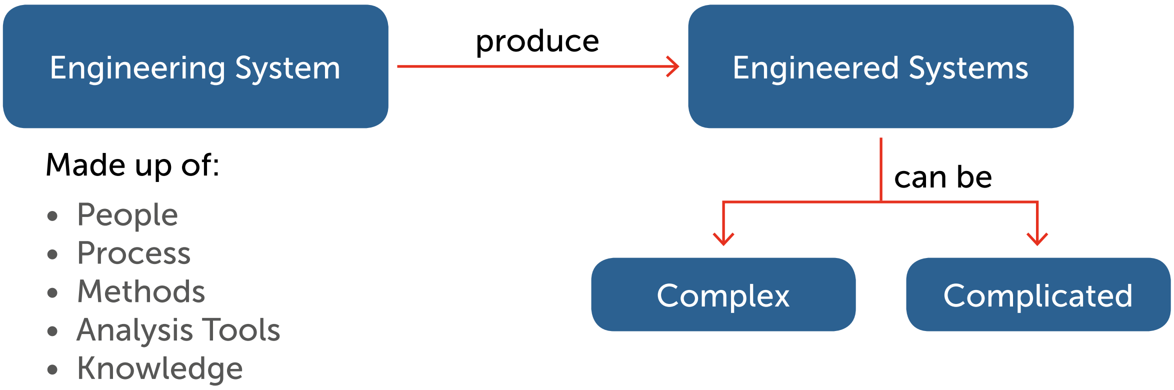


Figure 1 - A schematic representation of the relations between complex, complicated, engineering and engineered systems.

While the ENCORE scope is within the engineering system, the domains clearly point at engineered systems and their resilience. This section hence addresses Complex Engineered Systems but the considerations, extended to include processes and methods, can apply likewise to the engineering systems.

> ***Complex Adaptive systems have inherent capability to modify their behaviour in response to internal and/or external (environmental) events, without explicit engineering intervention. This capability of a system to "evolve", autonomously, in the operational environment, enables more generalised resilience, to a wider range of events.***

Complex and Complicated Engineered Systems

It is first important to understand what complex engineered systems means, and especially what is different about complex systems (as opposed to systems that are "merely" complicated), in order to engineer systems that fulfil the requirements and expectation of stakeholders, including society.

The concept of a "System" is key. A System is an assembly of components, interconnected in an organized way to form a whole, exhibiting properties and behaviour as a whole, distinct from and not necessarily predictable solely from the (combined) properties and behaviour of its components.

Engineered Systems can be complicated or complex. A complicated system has many aspects or components to consider, but nonetheless amenable to rational planning, design and execution, albeit, perhaps, on a large scale A complex system has many inter-related aspects or components to consider, each of which has its own (at least partly) autonomous or independent behaviour, influenced by interactions with other elements. The ("emergent") properties and behaviour of a complex system are not (fully) predictable, confounding many classical systems engineering techniques and methodologies.

The Concept of System

All systems share certain common defining characteristics; complex systems have additional characteristics. The general characteristics of systems, common to both complicated and complex systems, are[1]:

1. A system compromises a collection of interacting components [1];
2. The behaviour of each component is influenced by its interactions with others and with its external environment;
3. The coupling, interaction, flows, delays and feedback loops between components result in emergent properties and behaviour(s) of the overall system, different from those of the components
4. Individual component behaviours and the relationships between the components of a system can change over time
5. Systems have life-cycles: a system may be developed and changed during that life-cycle
6. Systems affect their environment and are affected by the environment in which they operate
7. When examined in detail, from different perspectives, a system can be viewed as both a component of a larger system and, itself, comprised of individual components
8. Systems contain multiple feedback loops with variable time constants, so that cause and effect relationships may not be obvious or easy to determine

Engineered Systems can be complicated or complex:

- *A complicated system has many aspects or components, but is nonetheless amenable to rational planning, design and execution, albeit, perhaps, on a massive scale.*
- *A complex system has many inter-related aspects or components, each of which has its own (at least partly) autonomous or independent behaviour, influenced by interactions with other components. The components are typically not subject to a common authority, have independent life-cycles, and may be able to operate as purposeful systems separate from the complex system.*

System Boundaries

The definition of the boundary of a system can be subjective or arbitrary; the engineered artefact may or may not be a true system (capable of independent useful function); but in engineering practice this is unimportant because it is the thought process of thinking of the solution as a system and the understanding that comes from that which is crucial.

Complex Systems are Different

Whilst complicated and complex systems have many characteristics in common, there are important differences[1]:

1. The boundary (physical and functional) of a complex system have a tendency to be more ambiguous than for a complicated system.
2. Components of a complex system can, themselves, be independent systems, whose development, operation and governance may be subject to different authorities – there may be no “top-down” overall control. These component systems can therefore have separate and independent life-cycles and, typically, there is no single top-level “Chief System Engineer” to whose authority all the component systems are subject.
3. The behaviour of each component of a complex system may be, at least partly, independent or autonomous [4]

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[1] Numbers in [] refer to headings in a list of characteristics of a complex system – “Two’s Company, Three is Complexity”, Johnson 2007

4. Emergent properties and behaviour(s) of the overall complex system cannot be fully deduced from those of its components alone [5,7]
5. The nature, occurrence and magnitude of emergent patterns of behaviour for a complex system can be unpredictable [6]
6. Emergent patterns of behaviour of complex systems frequently exhibit a mixture of regularity (order) and randomness (disorder). The transitional region between order and disorder is of particular interest [8]
7. Delays within components or to interactions between components, together with “loops” in the flows of interactions among component, induce (emergent) behavioural effects analogous to “memory” and “feedback” [2,3]
8. A degree of the complexity arises from the inclusion of the unpredictability of human (individual or society) behaviour. There are socio-technical aspects to complex systems, where the humans must be considered not just as users of the system, but as components within it.

Coupling, interactions, flows, delays and feedback loops between components of a Complex System result in “emergent“ properties and behaviour(s) of the overall system, distinct from those of the components. The nature, occurrence and magnitude of emergent patterns of behaviour of a Complex System are not (fully) predictable, confounding many classical systems engineering techniques and methodologies.

Complex Systems: Definition and Characteristics

Through the ENCORE processes, events and debates we define a complex system as “A collection of interacting components, each of which has its own (at least partly) autonomous or independent behaviour, influenced by interactions with other elements. The components are typically not subject to a common authority, have independent life-cycles, and may be able to operate as purposeful systems separate from the complex system”.

The definitions above are important as they allow to identify and characterise systems across domains, exposing practice and learning that can be shared between (for instance) ecosystems, jet engines design and infrastructure systems.

An individual system may, either permanently or temporarily, be part of (or a component of) a larger system, giving rise to a System of Systems. Typical characteristics of Systems of Systems are operational and management independence of their component systems, evolutionary development, emergent behaviours, and information-only interactions between component systems. These characteristics can lead to more unexpected emergence, making Systems of Systems more likely to be complex.

A complex system may have inherent capability to adapt its behaviour in response to internal and/or external (environmental) events, without explicit engineering intervention; this is termed a Complex Adaptive System. The capability of a system to “evolve”, autonomously, in the operational environment, may engender more generalised resilience, to a wider gamut of events. That same adaptation capability is likely to have significant impact on the conventional view of how engineering continues into the operational phase of a system.

One challenge with such adaptive approaches is that the limited predictability of the system (in some ways beneficial, for resilience) may hinder effective risk management, especially for extreme (but rare) events. Complex systems and the engineering processes supporting their development and ongoing maintenance need to cater for such uncertainty.

Lack of predictability may limit the usefulness of some traditional engineering practice in the development of complex systems. For example, although simulation can, often usefully, illustrate the kinds of behaviour that might be exhibited by a complex system, actual behaviour cannot be predicted, even if all initial conditions and subsequent external interactions are known precisely. The system behaviour may exhibit wild fluctuations, whose nature, occurrence and magnitude (e.g. in space or time) are unpredictable, posing a real challenge

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[1] Numbers in [] refer to headings in a list of characteristics of a complex system – “Two’s Company, Three is Complexity”, Johnson 2007

to the effective management of risk. Engineering processes for complex systems need to cater for such uncertainty.

The nature of complex systems and how they are different to complicated ones is important for four reasons:

a. Most engineering practice has evolved to cater for complicated systems (e.g. rockets, trains, aircraft, buildings). There is no established engineering practice to address particular characteristics – e.g. emergence by design and unpredictability – in the design of complex systems.

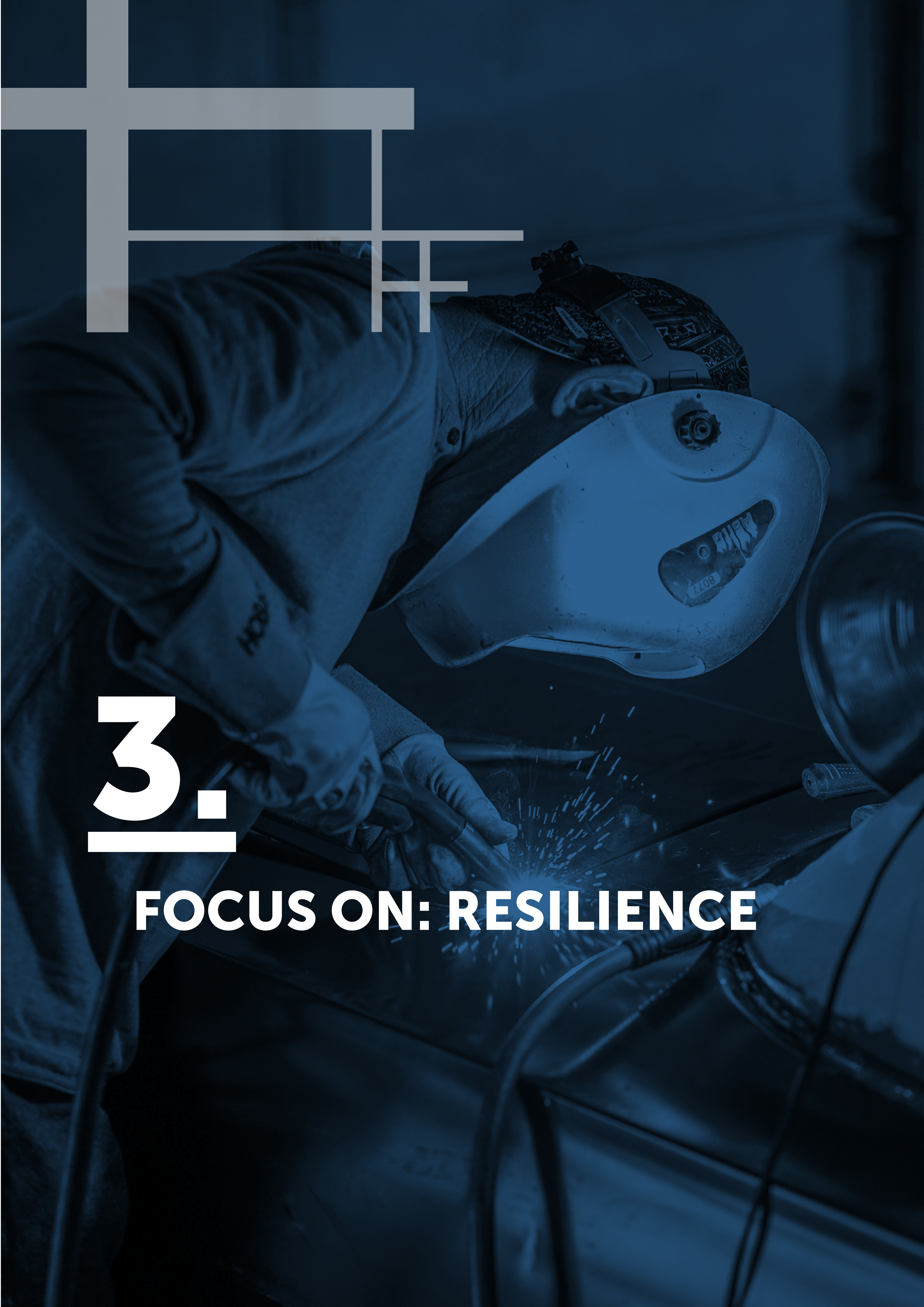
b. Complexity is different to complication – there is no established engineering practice, and worse, because of the difference between complex and complicated systems, the practice used to engineer a complicated system is unlikely to be sufficient for a complex system.

c. As a complex system is engineered and subsequently deployed into its operational environment, additional complexity will be introduced. The operational system will have to be resilient – both to variations and change in environment and usage (external factors); and also to the unpredictable emergence arising from the structure of the engineered system – so that society can benefit from, trust and depend on these systems.

d. Society is generally unprepared for complex systems, especially with the expectations of certainty and predictability that have grown up with standard, complicated systems. There may need to be a new relationship between Engineers and society around what is expected from Complex Engineered Systems – for example, with respect to safety or professional responsibility. Engineers (as people) and Engineering (as a practice) will need to understand the implications.

Traditional approaches to Systems Engineering have stood the test of time and have been successfully applied to the engineering of extremely complicated systems. However, for complex systems, many or all of the "crucial" assumptions on which the efficacy of conventional engineering methods, practices and systems depend are no longer valid. Complicated systems thinking is therefore inadequate for the successful engineering of complex systems and likely to result in undesirable or unexpected behaviours.

Engineers will have to understand the impact on society of the complexity and adaptability of systems. An understanding of both complexity and resilience, as it applies to engineered systems, is required so that effective engineering practice can be developed that can be practically used (see Section 5). Without this, the world will not be able to rely on the engineered systems needed for the sustainable quality of life desired. Unpredictable emergence from such systems may result in events whose impact on society is unacceptable.



3.

FOCUS ON: RESILIENCE

Resilience in Complex Systems

In general, resilience is not an inherent or inevitable property of a complex engineered system. In some complex systems, however, there can arise a process of “self-organisation”, a tendency for order to emerge spontaneously from interactions between multiple components, which can increase robustness and/ or resilience to shocks and stresses (and change the performance/outcomes of the system as well). Such characteristics tend to arise as a function of the degree of control decentralisation.

Temporal and topological aspects of patterns of interaction between system components enable changes to overall system behaviour in response to internal or external interactions. Typically, selection mechanisms favour persistence of those changes, the effects of which are evaluated as positive according to certain “success criteria”. Such selective processes underpin explicit “training” of complex adaptive systems, as well as their autonomous (or unguided) “evolution”. The engineered system is hence subject to continuous transformations changing its characteristics, which include its resilience.

The ENCORE Definition

In the context of ENCORE:

Resilience is the ability of a system to prepare for, mitigate, adapt to, and/or rapidly recover from the effects of endogenous and exogenous “disruptive” events.

The events do not need to be instantaneous and, as the definition states, can originate within the system. This is a characterising aspect of complex systems, where the unpredictability of behaviour is responsible for potentially hazardous behaviours emerging out of the interactions of the different parts of the systems, which would not behave as such in isolation. Whatever the event, the system resilience is defined by the processes that inform the system of the possible collapse disruption and help the system mitigate its consequences.

> *Complex systems evolve over time developing characteristics that could turn harmful to the system as much as external shocks and stresses. Resilience for complex systems has to account for both endogenous and exogenous disruptive events.*

An Essential Review of Resilience Definitions

The concept of resilience is mostly present in the modern scientific debate through the areas of ecology and psychology, although arguments have been proposed that link the current understanding of resilience to the engineering field (Alexander, 2013). In the first the focus is on the ability of species to survive extinction (Holling, 1973). The latter mostly referred to resilience as the ability of the human brain to bounce back from emotional shocks (Vernon, 2004), especially in childhood (see for example Werner and Smith, 1982). The two fields are distant and, as such, it cannot be expected that the same meaning is attributed to the word “resilience” in both contexts, let alone in engineering. On further scoping the literature, it becomes clear that resilience does not have an agreed definition even within the same knowledge area [Vernon, 2004, Fleming & Ledogar, 2008].

The word resilience has been used in a wide variety of contexts and often in substitutions for concepts such as robustness, redundancy, recovery, etc. There is a lack of consensus about the actual meaning of resilience. Popular definitions revolve around the concept of “bouncing back”, with resilience being the characteristic of a system able to restore its functioning or return to some performance level after having gone through disruptions [Hosseini et al 2016]. This approach offers an immediate way of measuring the resilience of a system hit by some disruptive event by combining the loss of functionalities and speed of recovery. In the context of community resilience, attention is placed instead on the ability to thrive through the hardship following the disruptive event [UNSRD]. This is sometimes indicated as long-term resilience. In both these approaches there is a clear time progression for the resilience evaluation that starts with the event striking the system. A cyclical view on resilience was proposed in the area of communications networks [Sterbenz et al 2010] with resilient systems being those able to defend against the rise of problems in the system, promptly detect them when they happen, remediate to their effect and recover being ready for the any future event. The EU-funded RESILENS project [Clarke et al., 2015] translates this into a definition that positions resilience as the cyclical application of risk assessment and management techniques. The RESILENS project considered the context of critical infrastructures and touched upon the aspects of complexity characterising such systems.

One Example for All: Aerospace

In space systems, the concept of resilience is related to the ability of the system to withstand one or more external disruptive attacks and preserve a given level of functionalities and services. The use of the term ‘attacks’ specifically refers to cybersecurity and space situational awareness, two key concerns of current and future constellations for telecommunication, earth observation and navigation. One interesting element in the concept of resilience is the idea of dynamically changing requirements, goals and constraints. (See for example Murray et al. [2013]). In civil aviation, resilience is often associated with the idea of system safety and includes elements of human error and the ability of the system to compensate for or recover from the occurrence of critical events [Netjasov & Janic, 2008].

Aerospace shares with other fields a popular feature in the characterisation of resilience: relating it to a particular event or to a class of events. In the context of communication networks, it is common to find references to resilience to node failures, while in the context of a community’s resilience, the focus is on natural disasters (floods, earthquakes, etc.). However, failure is sometimes originated by peaks of the system loads or by the accelerated wearing of the system’s components subject to long and sustained loads. The resilience of systems to their own functioning is even harder to address.

Resilience in complex systems requires a holistic approach that extends the limits of the system to include the appropriate causes of disturbances while keeping the problem manageable. What has to be including in the system’s boundaries and how comes from increasing awareness through the science underpinning complex systems.

Engineering Resilience in Complex Systems

Whilst ecology remains by far the subject area where the resilience concept is most widely used, engineering has begun to explore its utility in the design and management of engineering systems. This work started with evolving the ideas from the concept of risk and recovery (Alexander, 2013). It is easy to understand that as more parts are added to a system, the number of possible failure modes increases. However, the solutions addressed by a classical engineering approach foresee an even greater increase in system elements, with the addition of monitoring sensors, reconfiguration software and redundant subsystems.

There is no easy solution to this but we consider the best option is understanding the complexity of the systems before increasing it through new engineering. Complexity science has developed a number of methods and tools with which to model, and through models to understand phenomena such as network burstiness (the sudden increase of network activity) or percolation, diffusion of ideas or epidemic diseases, scaling laws that can be related to the growth of cities or the thriving of enterprises. These tools have to be adapted and used to address the resilience challenge. This poses a question about the limit of the system. The typical approach of complexity science is challenged by the external perturbations resilience is evaluated against.

A “holistic” approach would prescribe the inclusion within the system boundaries of the appropriate disturbances and no more. These can take any shape and form and are not even accountable under a unified view looking at their effects on the system. The disruption to public transport due to overcrowding is very different from a power failure halting the train, which can, in turn, be the cause for overcrowding of alternative transportation means.

When considering complex engineering and engineered systems, it is desirable that complexity science delivers an understanding of the system that prevents disruptive events from repeating themselves or mitigates their impact. By doing so, it will also improve the response to the immediate consequences of a disruption, helping to concentrate the efforts on the most effective system leverage points. The continuous learning superimposed over continuous application of risk assessment practice is represented graphically in Figure 2 and Figure 3.

Resilience definitions have been provided in a variety of scientific fields, from Ecology to Psychology. In Engineering its operative definition is linked to the recursive application of risk assessment and management techniques.

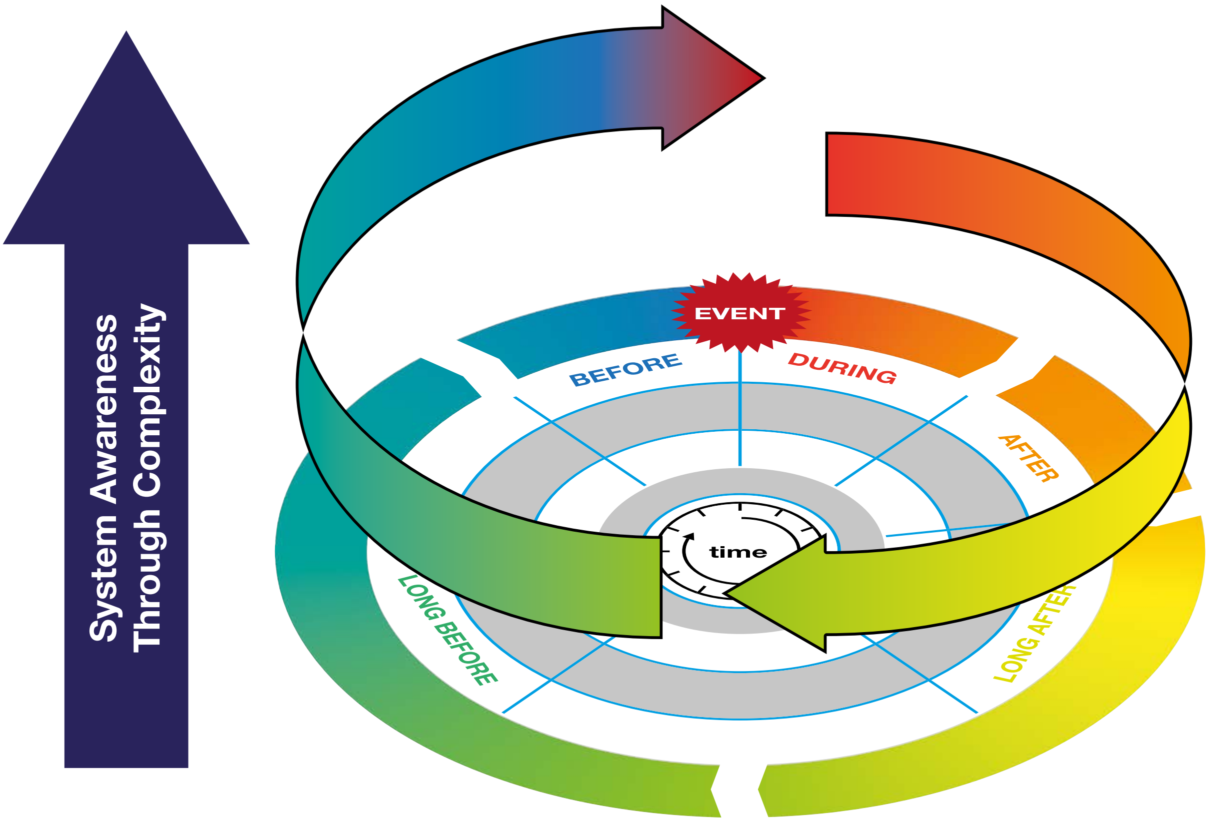


Figure 2 - Resilience diagram. The continuous application of risk assessment practice makes the system more ready for the impact of disruptive events. However, complexity science allows for increasing the understanding of the system hence providing an elevated view-point for the risk assessment practices. The diagram is elaborated from a similar version currently under review [Punzo et al. Under review]

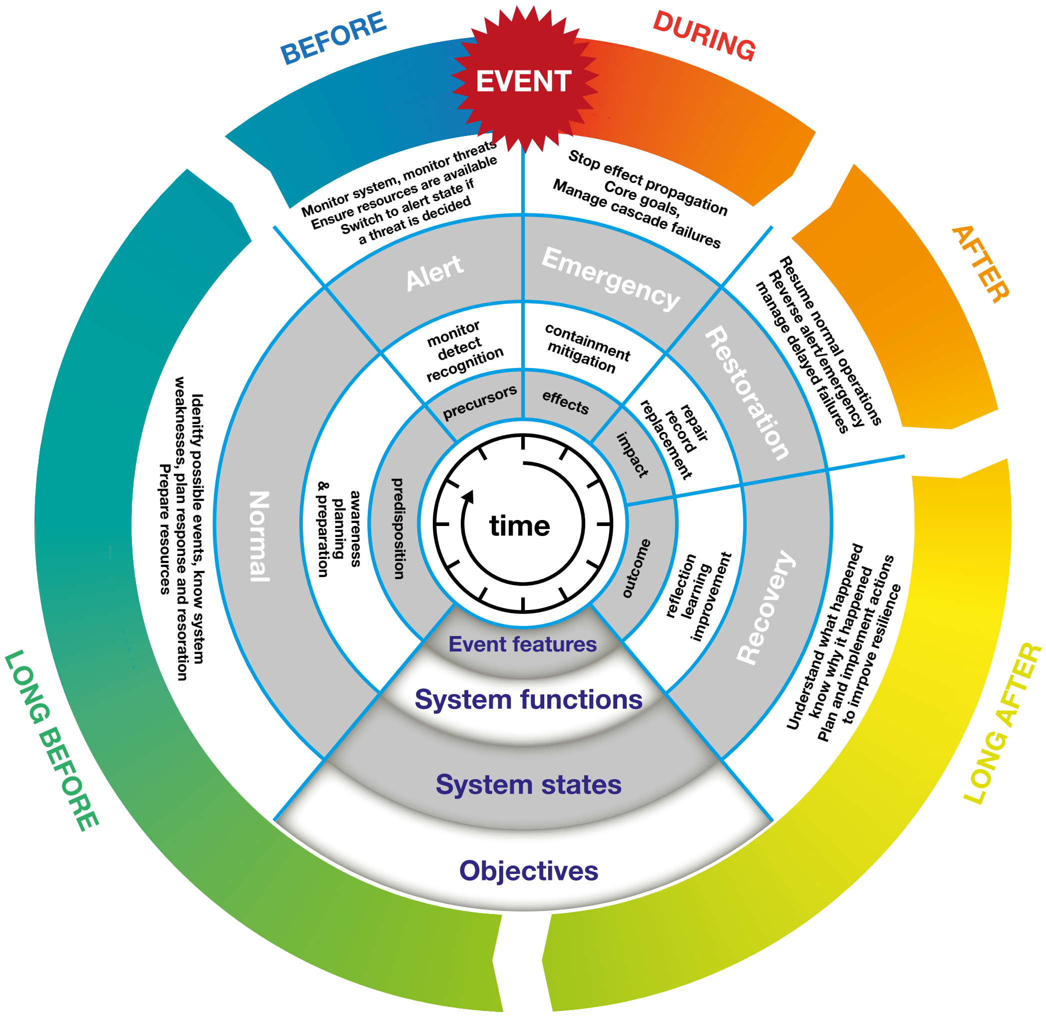


Figure 3 - Resilience diagram. The continuous application of risk assessment practice makes the system more ready for the impact of disruptive events. However, complexity science allows for increasing the understanding of the system hence providing an elevated view-point for the risk assessment practices.

Understanding, Modelling and Integrating Resilience in CES

Complexity science has been successful in developing modelling and analysis techniques for generalised abstract scenarios. Their applications to engineering systems has not produced a step change as very rarely these techniques have been developed to analyse the specific system and phenomena for which the resilience problem is posed. On one hand resilience should be contextualised within the system and the environment in which it is evaluated. On the other hand, the techniques used to understand the system and its resilience should be designed to address the specific system rather than being adapted from a general mathematical framework. As an example, while reductionist approaches fail to capture general characteristics of a transportation system, a network theoretic approach would fail to identify any resilience feature different from those of a telecommunication system, or of a supply chain. The literature on resilience exhibits a gap in the non-mediated application of complexity thinking to engineered systems with consequent development of methods and techniques specific to the systems.

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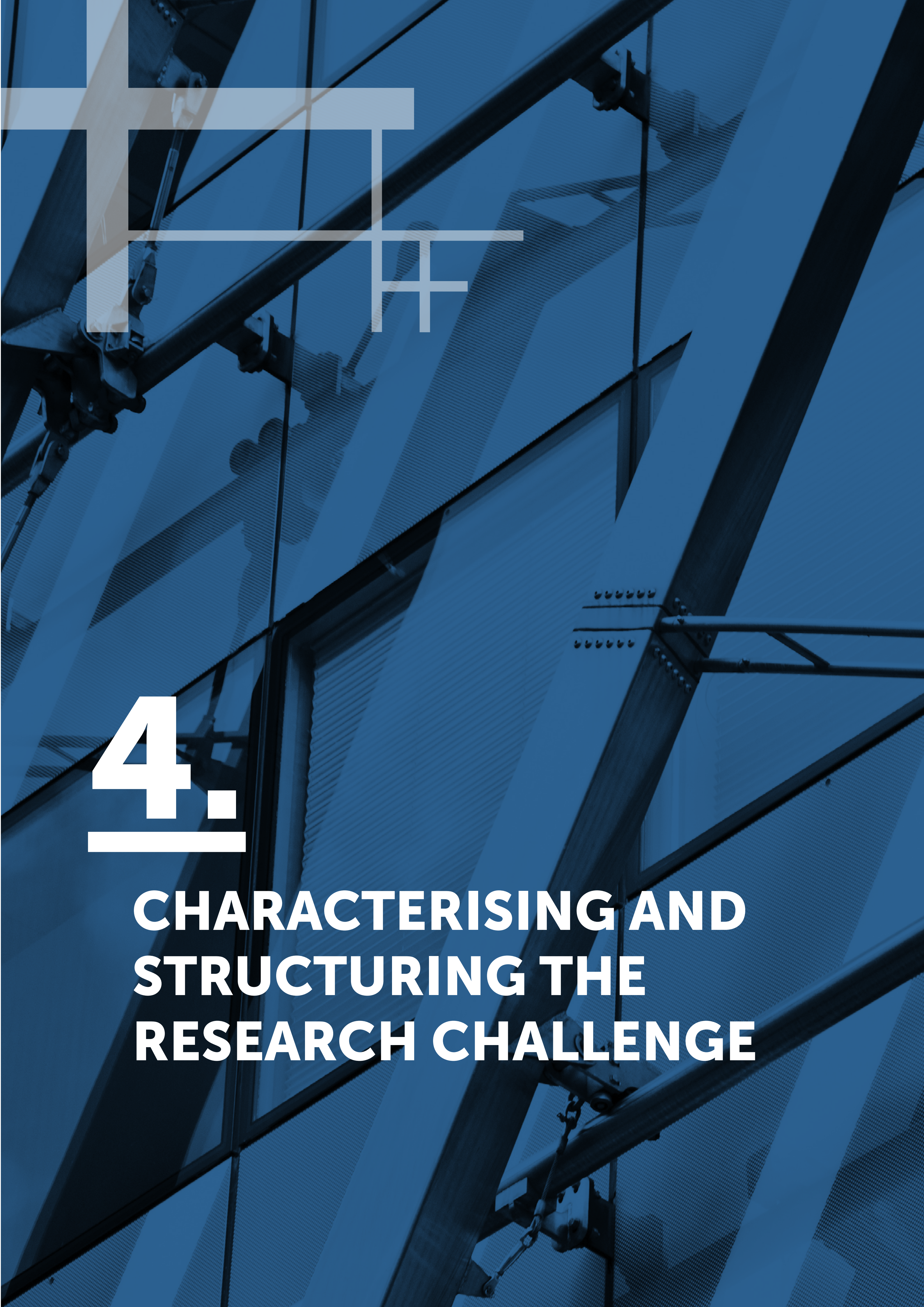

4.

CHARACTERISING AND STRUCTURING THE RESEARCH CHALLENGE

The activities of ENCORE have been structured to establish areas of shared meaning across several disciplines concerned with modelling/representing, understanding/explaining, designing/building and managing complex systems. The network is exploring how we develop a common understanding of the challenge between three core clusters; 1) Complex Engineered Systems; 2) Complexity Science; 3) Natural Complex Systems; in order to investigate the methods and applications of complexity science in the creation, development and operation of complex engineered systems. It is fully acknowledged that these definitions are permeable and fluid, representing a broad community of scientists and engineers and that social systems are both a natural complex system and the creator and user of CES.

This process is focused upon establishing the challenges in creating resilience in complex engineered systems and identifying the opportunities presented through the application of complex systems approaches to these challenges.

So far, the ENCORE network has identified the following specific challenges and opportunities. The work to date has identified four classes of challenge and three areas of opportunity within which we have highlighted specific research questions.

Challenges

Challenges are characterised as:

i. inputs or environmental pressures that influence complex engineering systems; and

ii. issues that arise as complexity emerges in the engineering systems and the engineered systems produced by them.

A feedback loop obviously exists from i to ii which is also included within our characterisation of the research field.

The challenge has four dimensions, [1] Understanding how system evolution affects resilience, [2] Understanding how Increasing complexity affects resilience, [3] how to design for resilience and [4] addressing the tension between performance and resilience.

System Evolution

The emergent behaviour of complex engineered systems is not well understood and poorly articulated in systems engineering texts [Sheard et al., 2015, Bar-Yam, 2003]. This might extend to the understanding of uncertainty, both in the environment (exogenous) and assembly (endogenous) of large Infrastructure systems and how the definition of such boundaries influences our understanding of CES.

The high-assurance product philosophy in aerospace, nuclear, rail and increasingly road transport can be paraphrased as 'Does what it says on the tin…. and nothing else!'. Proving this in an engineering sense is a real and significant problem, especially as the currently prevailing approach is to connect systems, irrespective of their underlying engineering regime. This has also a strong connection with the regulation problem driving design changes in sometimes questionable ways due to unforeseen issues of regulations.

This can be summarised as two complementary challenges, the first is cyber-physical, the second sociotechnical in nature:

- Bolting together legacy with new systems. How can a systemic approach to design of CES extract value and manage challenges arising from significant variations in sub-system evolution? This includes the challenge of how to create systems of a known reliability, with a diverse and changing set of components, often with an unknown reliability. A key issue here is avoiding the stifling of innovation if a system adopts a path where nothing can be upgraded until everything can be upgraded, which simply leads to stagnation.
- Evolving systems under different authorities. The US president's commission report on critical infrastructure defines these as "network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services" [President's Commission, 1997]. This definition highlights the clear conflict between pursuing a societal target (the provision of services) through agents that move in a market driven by private interests.

Increasing Complexity

Society is experiencing a rapidly accelerating integration of digital (cyber) and physical systems yet we have little real understanding of how these interact. Cyber physical systems (CPS) are “integrations of computation, networking and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa” (http://cyberphysicalsystems.org/). This has been suggested as connecting systems that operate primarily according to physical principles with those that operate in the digital domain. The integration of dynamics with very different speeds and scales can result in unexpected, catastrophic outcomes. CES, which underpin society, are evolving as cyber-physical systems. They are becoming increasingly complex yet our understanding of how they perform, how to optimise their design, how it responds to shocks and stress, is poor.

We should not wait for the inevitable major failures that will arise before we address this issue: we need to design systems capable of much higher degrees of resilience than currently considered. This is compounded by the scope comprising multiple systems, operated by multiple, independent authorities, with potentially differing and ill-coordinated policies and decision making paradigms and practices. What tools might help us understand interdependencies within and between systems?

Significant challenges have been raised relating to the broad area of Cyber-Physical System (CPS) resilience:

- How do we take advantage of hybrid cyber-physical systems (cyber, e.g. digital with physical) whilst managing the challenges of such integration? Control theory in this area is well developed but not applied to the more challenging case of evolving infrastructure systems).
- In physical systems, as connections increase, resilience is backed by redundancy. In digital and ecological systems, as connections increase, resilience tends to decrease (as connections work as means of contagion). This might relate to dealing with super-connectors in networks as it will differ widely for each type of system.
- Risks emerging from the global scale and speed of development (particularly digital and cyber physical systems). As an example, how do we verify Cyber-physical systems where the two sides evolve in different time and time-scales?
- How to explore different control hierarchies for CPS and their relative benefits (e.g. more centralised, more distributed, hybrid)?
- What are the driving characteristics of cyber-physical system evolution that requires new design tools to deliver performance and resilience gains?
- How do we mitigate design against unanticipated effects of increasing the complexity of systems?
- How do we design for the fact that digital systems’ resilience is often insufficient when applied to critical systems?
- In space systems, failure detection, identification and recovery systems are normally adopted. Are they sufficient? The general consequence is that systems enter safe mode very often and unexpectedly. In some cases, anomalies cannot be explained even after they occur and the system recovers.

In addition, the broad challenge of communicating complexity is a recurrent theme. Enhancing our Complex Engineered Systems requires that we understand and communicate systemic behaviour traits such as balancing and reinforcing feedback loops and how to encourage resilience-enhancing properties such as the emergence of self-organisation. This requires that we convey the complex nature of such systems. We currently do not have the tools and techniques to communicate such complexity.

Design for Resilience

The challenge of designing for resilience can be structured as how to design CES to manage:

- high impact, low frequency events;
- both cascading and multiple independent failures;
- be resilient to their own evolution and that of their environment, hence avoiding overdesign to develop and maintain some degree of flexibility through bounding uncertainty.

In order to design for resilience in CEdS, a key challenge is to establish the principles of complex systems that are useful in complex engineering designs. The work of ENCORE has begun this but a major research effort is required in order to establish generic and domain specific principles. Examples include:

- Looking beyond the components or systems being built to understand their context, interactions and the service that is required from them.
- Understanding the importance of heterogeneity and how to embed it within CES.
- How to design and operate Complex Engineered Systems to achieve controlled performance degradation and the convergence towards a sub-optimal, yet functional state that sustain systems functions in failure mode (elegant decline)?
- Examples of domain specific challenges relating to the design of CES include:
- Motivated, intelligent cyber-criminals (and saboteurs) will seek out weaknesses in CES that they can exploit. How do we respond to this challenge? Cyber security is a current area of research focus but CPS security is not. How do we leverage the physical design properties to increase resilience as these systems evolve?
- Predicting power grid frequency considering the influence of human drivers, local weather, traditional generation failures, embedded generation and renewables.
- Limit the vulnerability of future and present satellite constellations providing critical services (like navigation).
- Manage space traffic to avoid catastrophic events with cascade effects.
- Achieving higher capacity from rail transport infrastructure without increasing vulnerability to 'knock-on' effects across the network from any perturbation to operations.

Although categorising is necessary for humans, it becomes pathological when the category is seen as definitive, preventing people from considering the fuzziness of boundaries, let alone revising their categories. The ENCORE experience has exposed a number of questions that have surfaced multiple times, one of which is how do we define what is important (e.g. certain nodes/edges, rules, behaviours etc.) under increasingly severe failure modes/reductions in CEdS performance?

> ***We should not wait for the inevitable major failures that will arise before we address this issue: we need to design systems capable of much higher degrees of resilience than currently considered.***

Other domain-free challenges that are the subject of ongoing work are:

- How does the manner in which we measure resilience change the perceived best design? For example, does the argument for energy storage change with the need to increase resilience as CES (such as the energy system) both increase in complexity and decrease in component performance over time?
- Spotting unusual behaviour in CES. In particular, how do we design CES in cases where we have significant quantities of data but very few (or no) instances of failure (which provide an insight to how systems behave prior to failure)?
- In a highly distributed and highly interconnected network, where hypotheses can be formulated on the cooperation or competition of the players within it, are there practicable strategies for a) bounding the impact of anomalous external behaviour on local nodes; b) bounding the "amplitude" of emergent behaviours – e.g. in response to shocks?

Performance-Resilience Tensioning (and Whole System Optimisation)

Systems under societal pressure over time will tend to create optimised rather than resilient solutions: the system performance is associated to the ability to deliver objectives in a fast and inexpensive fashion rather than doing so in the presence of disruptions. This creates a concentration among a few nodes that serve as central connections. Social networks have a natural tendency to organise themselves around a small worlds architecture – a few nodes are extremely well connected, others barely so. This makes systems more robust but also more fragile as they are more vulnerable to major node failure. Therefore, the challenge is how do we develop our CES? For instance, this could suggest more, smaller, more diverse sources of energy. This idea would be contrary to the current thinking on mixing large providers (nuclear power stations) with a wide range of smaller energy source and suggests that large nodes are avoided. Is this a valid thesis? We may learn from analysis of strategies in the air control sector which is increasing autonomy in traffic management and the rail sector which is increasing centralised control, as both aim to increase resilience in their complex networks.

Systems under societal pressure over time will tend to create optimised rather than resilient solutions.

This raises three particular challenges:

- As resource demands increase, the need to pursue whole system optimisation rather than sub-system optimisation will increase. Complexity science suggests this will further compromise systemic resilience. How do we manage (and benefit from) designing for interdependencies across CES, scales and components?
- What is the relationship between optimal and resilient performance? How does this vary as the heterogeneous nature of systems of systems expands? How do we explore how solutions that might be performance-optimised work under various degrees of stress / scenarios of shocks?
- The impacts of CESs on the natural world are often devastating and widespread. By leveraging on the natural ecology, CES can impact negatively on their own resilience by imposing transformation on the biosphere and social networks. The challenge is hence to enhance resilience through minimising the environmental impact of CES.

This paradigm of resilient CES suggests that:

1. We measure resilience a priori rather than a-posteriori and through a non-circular logic. This is strictly linked to the set of threats to resilience included in the system boundaries.
2. We discard the fully designed approach and accept instead the full understanding of reality. This means expecting that a system fails, sometimes. Yet we build an understanding of why and how this can happen, that is, we manage to frame the unknown unknowns, which may originate from within the system, and stay prepared to bounce back from the disruption.
3. The level of uncertainty about the system complexity can be taken as a measure of the system resilience (the less it is known about how the system works, the slower and patchier the response to its disruption).

Opportunities

Opportunities become available from the adoption of a Complex Systems approach. The opportunities arise from both blue sky ideas and translating methods across domains.

Bio-inspired Systems Architecture and Strategies

To what extent does or doesn’t nature favour centralised network structures? Biological systems can adapt their structures over time in order to maintain their functional properties; why do we observe such a wide variety of biological structures under essentially the same environmental conditions? In ecosystem models it has been found that trophic coherence favours stability [Johnson et al, 2014], can this concept, through industrial ecology, help governing the energy market towards a solution to the energy trilemma? Is there any way to translate evolutionary dynamics into engineering acceptable processes, that is, without sacrificing systems (or species) for the survival and resilience enhancement of the whole?

Experiences such as Chaos Monkey[2] seem to test some cyber system resilience in this sense, yet the way to expand this to more general systems is still to be found.

Design to benefit from developmental constraints

High-order CES such as cities or infrastructure systems exhibit constraints that are often not considered in the models used to predict their behaviour. Processes such as aggregation and self-organisation create temporal and relational constraints. We need to understand how such developmental constraints relate to design and performance in order to benefit, rather than suffer, from such characteristics [Thompson 1917; Kauffman 1993; Goodwin 2001]. As an example, we are beginning to understand developmental constraints in the growth and morphology of cities [Batty 2005] through exploiting understanding of the behaviour of complex systems. At present this understanding is focused on the physical properties of cities. Significant opportunities to improve resilience and performance lie in the potential to extend this understanding into the underpinning engineered systems and social structures. Opportunities exist to extract the design principles that define beneficial attributes and behaviours in naturally complex systems and use this to inform the design of socio- technical systems. As an example, Advanced Energy eco-systems, often referred to as Smart Grid 3.0, will require

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[2] http://techblog.netflix.com/2011/07/netflix-simian-army.html

the properties of self-organisation, self-repair, robustness and adaptation characteristic of naturally complex systems [Carvallo, Cooper 2011].

The key difference when comparing CES across domains is constraints. Financial systems have more flexible constraints (regulations) compared to infrastructure, having to deal with spatial embedding. Can patterns of behaviour be found between how markets behave and the much wider range of wavelengths (parameters) of infrastructure systems?

What are cross-domain behaviour traits? Can the behaviour of ecological or biological systems be seen in the infrastructure systems across temporal scales?

We are poor at evaluating Infrastructure Systems for their performance under extreme shocks and stresses. An interesting parallel is banking. Stress testing of this system has leapt forward following the crash of 2008. The financial systems are now tested under much more extreme scenarios (although arguments cab be made on the vulnerability to internally generated shocks). Techniques such as extreme value analysis allow researchers to explore uncertainty in financial system models. Is this transferable research? Further parallels with banking exist in how resilience may be increased - banks are required to hold greater reserves, just as a transport network may build in extensive recovery time to mitigate cascade of disruption, but understanding is lacking the trade-off between the increased resilience achieved and reduction of efficiency in these systems.

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Managing uncertainty in Complex Engineering (and Engineered) Systems

A challenge for engineers exists in their ability to alter and control the behaviour of existing CES to have predictable performance under uncertainty and detect when this does not happen. Whether this is reconfiguring an energy system to accept a dynamic mix of generation types or updating software in communication networks, the implementation of minor changes can have multi-scale cascading impacts upon systemic behaviour and performance [Newman, 2011]. Over time multiple changes are a record or description of the drivers of emergence behaviour in such systems. We need effective tools to deal with uncertainty when the identification of all statistical properties of a system is extremely difficult due to its complexity. The emergence and propagation of uncertainties through complex systems can compromise the understanding the degrees of redundancy and resilience of a network. Complexity Science offers the opportunity to develop new techniques to advance the understanding of transitional characteristics to develop our ability to predict such failures [Scheffer, 2009]. In this sense, it is fundamental to understand system structure and dynamics in a socio-technical context, since system design is often undermined by unexpected behaviour of humans in situations of high uncertainty.

5.

CHALLENGES OF TRANSLATING SCIENCE INTO ACTION

Complex Engineered Systems are produced by Complex Engineering Systems: single or groups of organisations embodying appropriate methods and processes and resources (including people). Complex, invariably highly interconnected systems are creating a new engineering landscape in which few of the traditional certainties or absolutes remain as solid foundations for engineering practice. Engineers will need to engage more in terms of 'expectations, operational range, and probabilities'.

Section 4 described four classes of challenge that arise as complexity emerges in the engineering, deployment and operation of complex systems. This section focuses on how complexity challenges traditional approaches to systems engineering and will thus necessitate fundamental changes to our Engineering Systems, methods and processes, informed by insights from Complexity Science. Education and training for future engineers will not only need to reflect these changes but also equip them to address the "softer" issues that result from the lack of full predictability of complex systems.

The Demands of Complexity on Engineering Systems

Complex Engineered Systems are produced by Complex Engineering Systems: single or groups of organisations embodying appropriate methods and processes and resources (including people). Complexity science and theory provide insights into the nature of complex systems and factors affecting their resilience. That understanding has to be converted into methodology, guidance and recommended practices which can be implemented in Engineering Systems.

The traditional Systems Engineering approach, e.g. top-down sequential design, typically decomposes (relatively stable) requirements, recursively, into simpler, comprehensible elements for which solutions can be designed; the overall system solution is synthesised from the elemental designs.

This process depends on the crucial assumptions that: a) system requirements can be decomposed into elements, each of which can be considered (largely) in isolation; b) the overall system can be synthesised from solutions to elemental requirements; c) properties and behaviour(s) of the overall system can be fully deduced from those of the elements alone.

The traditional approach to Systems Engineering has stood the test of time and has been successfully applied to the engineering of extremely complicated systems. However, for Complex Systems, many or all of the "crucial" assumptions on which the efficacy of conventional Engineering Systems depend are no longer valid.

The properties or behaviours of a Complex System may be quite unlike those of its components. Critically, the nature, occurrence and magnitude of (emergent) properties or behaviours of a Complex System may not be predictable in terms of those of its elements, thwarting many traditional design and verification techniques.

Continual change of immediate system requirements and of the environment or context in which the system must operate further challenges established methods, especially for (complex) systems capable of self-adaptation in response to events in their environments.

Engineered systems solution will increasingly be required not merely to cope with complexity – for example, inherent in the environments in which they operate – but also to embrace and exploit the benefits of features associated with complexity, such as adaptability and self-organisation. Design emphasis will shift from copious prescriptive detail to

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specification of minimal objectives and constraints, with the minutiae supplied by the Engineering System (during design) and/or the Engineered System (during operation).

There is a need for new engineering approaches, methods and tools to cater for circumstances in which system requirements and engineering solutions may be dynamic, uncertain, inexact, not fully deterministic and not exhaustively verifiable. These fundamental changes to systems engineering will necessitate different ways of thinking about systems, their design and operation; correspondingly new tools and methods will be required, to support these engineering activities and associated tasks. They must be informed by Complexity Science and incorporated into education, training and professional development for engineers.

> ***Engineered systems solution will increasingly be required not merely to cope with complexity but also to embrace and exploit the benefits of features associated with complexity, such as adaptability and self-organisation. Design emphasis will shift from copious prescriptive detail to specification of minimal objectives and constraints, with the minutiae supplied by the Engineering System (during design) and/or the Engineered System (during operation).***

Additional Complexity Challenges for Systems Engineering

Modelling, Simulation and Validation

The fidelity with which a system can be modelled is always limited by the completeness and accuracy of the system description from which the model is built. The lack of predictability inherent in the emergent behaviours of complex systems, particularly complex adaptive systems, places additional limits on features that can be accurately (and quantitatively) modelled. Even with extensive simulation, results may be qualitative rather than quantitative or exhaustive.

It is often impractical or too risky to use the “real world” in order to test isolated and immature engineering assumptions, until sufficiently and confidently validated. Early validation often attempts to use an ‘unrepresentative’, but ‘sufficiently representative’ model of the system for the behaviour under test. The engineering task then includes assessing the extent to which the test system is representative, transforming the results and extrapolating them for the real environment.

This traditional Systems Engineering approach depends on assumptions of “linearity” or “continuity” of behaviour, so that extrapolation from validated results to the reality is well founded. For Complex Systems, this approach is less plausible, not least as a consequence of their emergent behaviours.

Requirements and Trade-offs

Non-functional requirements place substantial burdens on the complexity of the engineering process and on the complexity of the final engineered product. This is particularly true for “critical systems”: systems whose failure can have far-reaching impacts – for individuals, for particular organisations or for wider reaches of society, the economy or national security. Particularly challenging for complex systems is the need to make “trade-offs” between different system aspects, including non-functional attributes, which are not readily reducible to a single (one-dimensional) metric (e.g. cost) and therefore not easily comparable.

Complex Systems often exhibit phenomena that are not precisely (mathematically) predictable – for example, emergent behaviours, non-linearity or discontinuity in some boundary region. These not only complicate the “trade-off” process but may also necessitate additional solution elements to mitigate the lack of full predictability – for example, introducing other independent systems, or using feedback, learning, or an ability to adapt and evolve (in many cases with the support of the engineering system). Such strategies help to ensure that the overall system is sufficiently robust or resilient to meet the (possibly changing) solution needs and environmental constraints.

The effectivity of engineering solutions over time is reducing because the pace of change (technology, materials etc.) is accelerating. The resulting trend of decreasing product life-time may be at odds with the additional engineering effort entailed by increasing system complexity and more frequently changing requirements.

Converting Scientific Knowledge to Engineering know-how

Complexity Science is creating new understanding of the nature of complexity and complex systems. This knowledge must be leveraged to transform our Engineering Systems, to address the inadequacies of that approach. The process of transferring and, where appropriate, translating that scientific knowledge into engineering guidance and practice needs to reflect several considerations.

The objective of science is to create explanations – "theories" – for phenomena observed in the world. Scientific results, on which explanations are based, must be reproducible to be independently validated and corroborated to be of (scientific) value. In contrast, the value of engineering solutions lies in the impracticality of obtaining the same results in a different way. Engineering solutions must be protected to realise the return on investment.

Scientific experiments are usually conducted under controlled laboratory conditions, in sharp contrast to the "messy" real world in which engineering is practised. Commercial competition creates business incentives for industrial engineers to investigate small changes to design parameters to improve the benefit(s) of the system relative to its cost.

Such incremental benefits may, in practice, include reduced design margins. Complex systems introduce further, risk-related issues into the overall assessment of such benefits: a) impacts of events on external systems and their stake-holders may not be negligible; b) the nature, occurrence and magnitude of events may not be manageable with conventional risk management methods.

Scientific and engineering communities need to work together to identify how the insights and theories of Complexity Science can be translated into practical engineering guidance and methods to address the challenges (and opportunities) of complex systems in the real world.

Social Change – Educating our Engineers

Complex, invariably highly interconnected systems are creating a new engineering landscape in which few of the traditional certainties or absolutes remain as solid foundations for engineering practice.

Engineers will need to engage more in terms of 'expectations, operational range, and probabilities'. From these less prescriptive specifications, they will still need to create solutions whose efficacy meets stake-holders' requirements or, at least, an acceptable trade of benefit versus cost and risk. These trade-offs may well need to include social, political, ethical, temporal (future generations) considerations which entail judgements in which a wider gamut of society, not just engineers, need to participate.

The culture, values and expectations of the society, the consuming public and especially nascent engineers will therefore need to change regarding the teaching and education of engineers, and what we expect them to be able to design/deliver (in terms of 'engineered solutions').

> ***The culture, values and expectations of the society, the consuming public and especially nascent engineers will therefore need to change regarding the teaching and education of engineers, and what we expect them to be able to design/deliver (in terms of 'engineered solutions') to create solutions whose efficacy meets stake-holders' requirements or, at least, an acceptable trade of benefit versus cost and risk, quality and safety, privacy and security.***

Educational and professional development programmes will need to incorporate both theoretical understanding, from Complexity Science, and its practical application to engineering problems. An EngD approach (rather than the traditional PhD) may present an opportunity for the educational side.

The challenges of making such changes in an existing engineering culture and environment should not be underestimated: the experience of those in a position to lead change will be with complicated (rather than complex) systems and there may be emotional ties to the conventional Systems Engineering approaches.

6.

KEY INVOLVEMENT AND RESPONSIBILITY FOR IMPROVING RESILIENCE OF CES

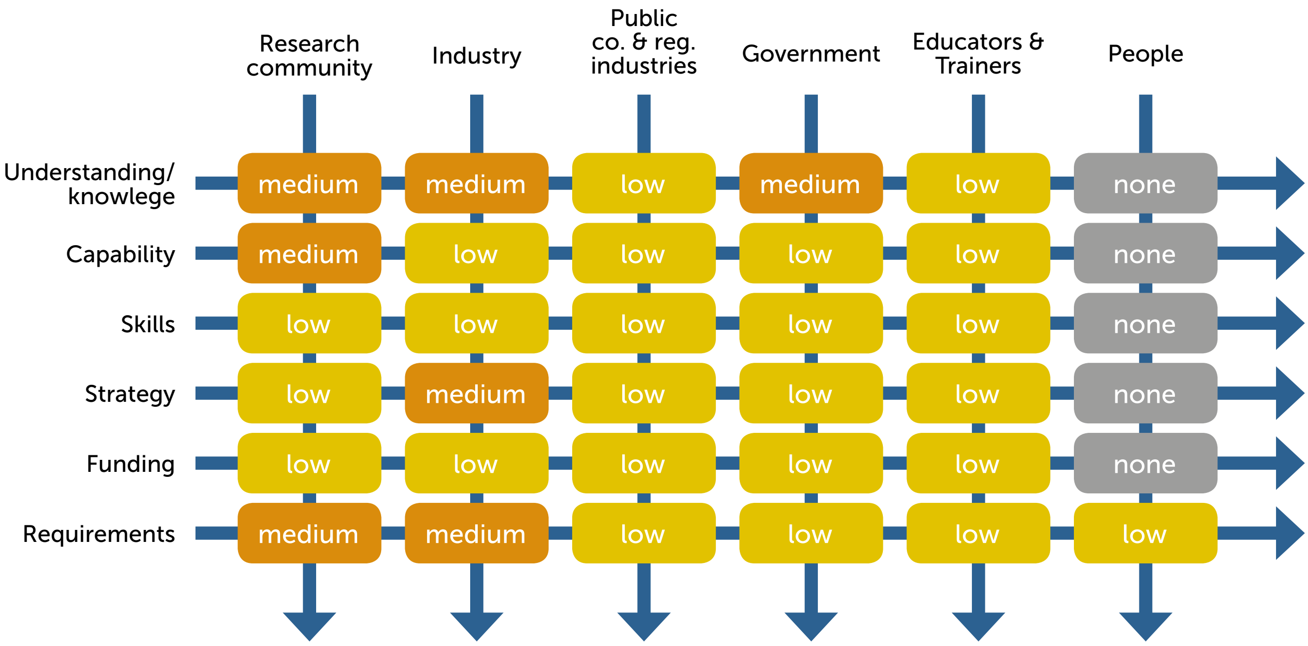
Introduction

It is important in further developing our understanding of the resilience of systems that are at the heart of our products, services and surroundings, that the key roles of those involved (knowingly or not) in complex engineering systems are identified and explained. ENCORE has identified six classes of key stakeholders, namely: [1] the research community; [2] industry; [3] public companies and regulated industries; [4] government; [5] educators and trainers, and [6] the general public.

ENCORE has also considered the involvement and actions of the different stakeholders. These are: [a] increasing the understanding and the knowledge; [b] capability; [c] skills; [d] the formulation of strategies; [e] the provision of funds, and [f] the definition of requirements.

In this part of the paper we seek to expand on the role the stakeholders might play in developing this field, as separate groups but, more importantly, in collaboration, to better reflect the inter-dependencies that realistically exist in today's complex, interconnected society. We summarise the assessment of the future stakeholders current involvement and responsibilities in Figure 4 and discuss their future involvement in the remainder of this section, with Figure 5 summarising the proposed level of responsibilities for taking action . Appendix 2 provides the detailed explanation of the key groups identified by ENCORE.

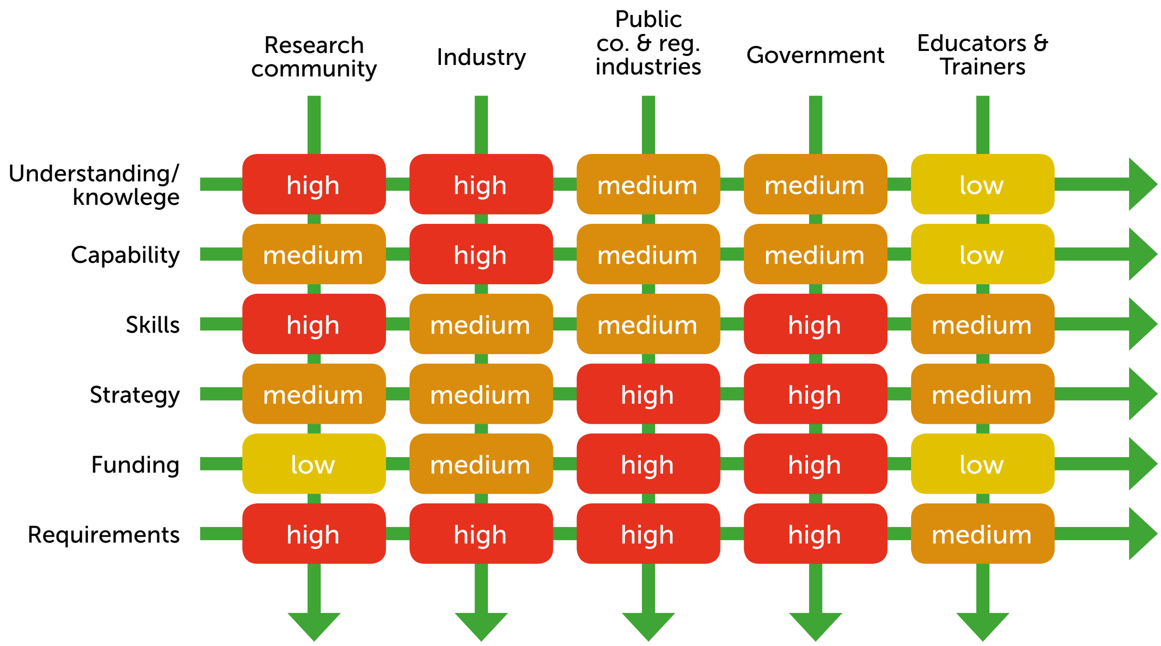
Existing levels of Involvement/Knowledge in CES



	Research community	Industry	Public co. & reg. industries	Government	Educators & Trainers	People
Understanding/ knowlege	medium	medium	low	medium	low	none
Capability	medium	low	low	low	low	none
Skills	low	low	low	low	low	none
Strategy	low	medium	low	low	low	none
Funding	low	low	low	low	low	none
Requirements	medium	medium	low	low	low	low

Figure 4 – Matrix representing the existing level of involvements of stakeholders in different aspects of CES

Proposed Levels of Responsibility for Developing Use of CES



	Research community	Industry	Public co. & reg. industries	Government	Educators & Trainers
Understanding/ knowlege	high	high	medium	medium	low
Capability	medium	high	medium	medium	low
Skills	high	medium	medium	high	medium
Strategy	medium	medium	high	high	medium
Funding	low	medium	high	high	low
Requirements	high	high	high	high	medium

Figure 5 - Matrix representing the responsibility by stakeholder for taking action

Understanding/Knowledge

ENCORE pioneered the challenge of bringing together the community of experts, practitioners and students of complex engineering systems. It has been developing the understanding of how complexity science can be best applied to improving resilience in fields such as infrastructure, cities and more general complex engineered systems. By involving a wider network of the research community with industry/public companies the project has been able to identify the key areas for future development. It has also exposed the limited understanding of how complex engineered systems can be designed, developed and operated.

The lack of knowledge and coordination between the key stakeholders to recognise when complex systems exist and how they can be made more resilient has also been revealed. Without a considerable improvement in this area the ability to substantially change the role of complexity science in complex engineering systems cannot happen and the benefits that could be gained will not be realised. An important challenge exists for the research community to work with trainers and educators to identify how understanding and knowledge can be best passed on to the wider groups in a structured way.

Capability/Skills

There is a long-standing problem with the depth and breadth of skills and capability in the field of complex engineering systems which has affected how knowledge and involvement in CES is utilised in all the groups. The ENCORE project has been a positive step in both growing the community of early career researchers and raising the awareness in other groups about the role CES can play in improving resilience. What has become evident is the importance of the research community in increasing support to Industry, Government and other groups by growing and applying the knowledge and understanding of how Complexity Science can be applied.

> ***In identifying who has responsibility for improving resilience in Complex Engineering Systems, six classes of stakeholders have been identified and a view on the relative responsibilities and actions of the groups has been proposed.***

Current numbers for research students and early career professionals in complexity science in the UK are not quantifiable because of the current lack of consensus on what defines a complex system in the research community. ENCORE has funded 11 feasibility studies in CES and developed a growing network currently counting 140 members. The intention is to create a pool of knowledge that can serve other groups with priorities of building capability and identifying useful methodologies that can be useful in the short term. The challenge is to build on these early efforts and give greater emphasis to bring in others who may help grow the levels of skills required.

As pointed out in Section 5, quantitative data about the expertise of those experienced in CES in industry and other groups are blurred but the industry partners working with ENCORE have identified low levels of knowledge within the more generalised group of system engineering graduates who join their organisations. Equally, other than in very specialised areas of industry, such as advanced research (Aero engines, IT) skills and capability in CES are very low if not non-existent (Stupples, 2007). This lack of capability and skills is critical in holding back the value that could be created by industry and government in improving resilience of infrastructure in many sectors.

> ***The lack of knowledge and coordination between the key stakeholders to recognise when complex systems exist and how they can be made more resilient has also been identified.***

Internationally there are indications of knowledge and capability in CES dating back a decade, including application in policy areas. An example is the OECD Global Science Forum in September 2009, including works on Applications of Complexity Science for Public Policy. However, this is an area that should be investigated to see how international experience could help in building skills and sharing the learning. Working with those who develop core educational qualifications in higher education will be important to identify how best to improve existing training and courses to deliver what is needed for the future.

> ***There has been progress in building a network of early career researchers but there remain significant concerns about the capability gap for engineers who work with complex engineering systems. Without changes in the way engineers are trained there are major risks in achieving improved resilience of complex engineered systems.***

Strategy

Government's policy for domains such as infrastructure has recognised the need to create a long-term view of what and how resilience should be improved for key sectors to meet industry and the public's growing concern about resilience. The increasing complexity and interdependence of infrastructure means that Government has the key role in creating policy in this area. Through EPSRC, it has sponsored many programmes and projects looking at various aspects of resilience, including ENCORE, focusing on complexity science to enhance resilience in engineering. Additionally, in the current 5-year strategic plan for EPSRC a key strategy for building capability is an important umbrella for further funding the capability gap that has been identified in CES.

What now needs to be developed is a longer-term strategy with industry first (but eventually involving the other stakeholders) on how best to reduce the capability gap and identify the methodologies for CES that best meet the needs of industry and society. The aim must be to provide more reliable and predictable services to people that are sustainable as systems become more complex. Such a strategy should be consistent with the growing number of strategies Government has been producing and lead to the action planning within which a long-term research strategy for CES can be developed. Clarity in policy and strategies will enable research priorities to be agreed across a wider grouping and focussed research programmes to be undertaken more readily.

Funding

Whilst the need for Government research funding in CES has been identified in the short term, (EPSRC has currently committed £6.7m of a £29.3m programme on Complexity Science to the engineering field), there is a need for a longer-term approach that should also involve those other groups/bodies who have an interest in this area. The priorities for research identified by ENCORE (see Section 4) will help EPSRC in the opening and awarding of large grants, and could become instrumental in seeking funds from other sources identified from the promotion of the ENCORE findings.

As there is no central source for collecting data on funding of research by industry and others outside Government, it is not evident what scale of investment could be made by these bodies to address the CES issues that are arising. Equally funding for higher education and skills training has many demands so the scope for adding further detailed requirements in these areas will need to be agreed. Creating a long-term source of funding which meets the future ambitions for growing CES therefore represents a significant challenge. As above, a clear policy and strategy will help to identify and quantify the need for research and training, which should be the basis for Government and other bodies to plan their funding requirements.

> *A key role for ENCORE has been to identify the priorities on which requirements for the future can be determined. Those priorities identified in this paper are around building capability and highlighting the most useful methodologies within complexity science in the short term.*

Establishing and Setting Requirements

As illustrated in Figure 5 there is a role for all groups to develop the understanding and use of CES. Figure 4 has been used to illustrate the various levels of involvement that have been assessed by ENCORE. In considering who is responsible for setting requirements, Figure 5 suggests there is a role for all the identified groups, but with a lead role for the research community in education and industry, because of the level of understanding currently available in these groups.

To achieve progress, a key role for ENCORE has been to identify the priorities on which requirements for the future can be determined. Those priorities identified in this paper are around building capability and highlighting the most useful methodologies within complexity science in the short term.

Working across groups is the key to developing a pool of knowledge available to industry/government which can then be utilised to establish the long term objectives in response to the challenges highlighted here. Overcoming silo thinking and working will be essential to deliver the solutions for the effective use of CES across sectors.

7.

STRATEGIC RESEARCH AGENDA - AN OUTLINE

This section provides recommendations for future activities, including a suggested prioritisation for how these could be addressed and outcomes made available to industry/policy makers (including a discussion of activity costs and where funding may be best targeted). This section will outline the research roadmap and be shaped to speak to funding bodies and industry.

The objective is to define and prioritise the research opportunities arising from the challenges facing CES using the ENCORE Resilience framework shown in Section 3 to structure the methodological approach as a function of the relationship to systemic shocks and stresses. A complete roadmap will be constructed, starting from this paper and considering the work undertaken in exploring the state of the art and methods explored in the previous two ENCORE papers, together with our feasibility studies, workshops and structured interviews with network members.

This section presents the outcome of the internal consultation within the writing group that will shape the axis along which the roadmap will move.

N2 Diagram

Method

The N2 diagram is a popular tool in systems and software engineering to specify and highlight the interfaces between different areas of a project. In this paper, the N2 diagram has the four challenges as rows and columns. With reference to Section 4, the challenges are.

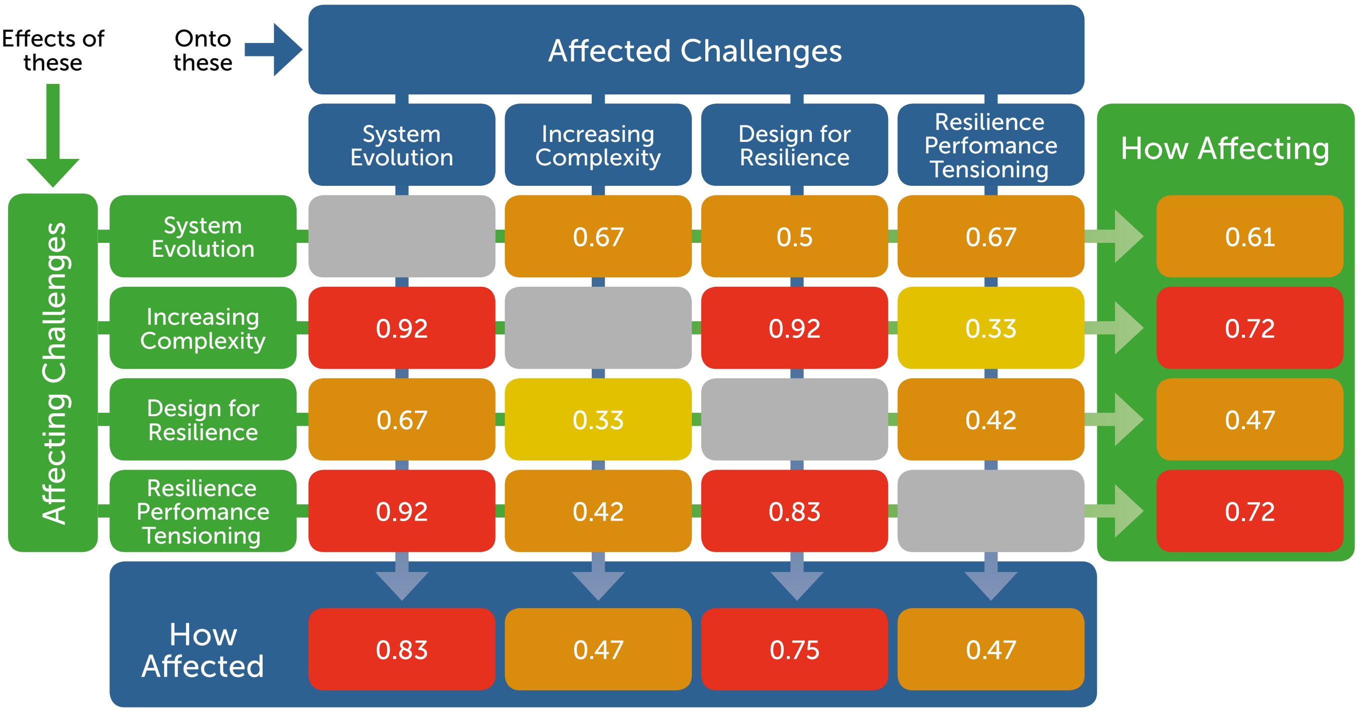
1. System Evolution (Abbreviated SE)
2. Increasing Complexity (IC)
3. Design for Resilience (DFR)
4. Resilience/Performance Tensioning (RPT)

The diagram is hence composed of 16 cells where each cell considers the effect of the challenge of the row on the challenge on the column: e.g. the cell at row 1, column 2 represents the effect of challenge 1 on challenge 2. We concentrated on the interface and reciprocal influence of the challenges rather than the challenges themselves as these were already covered in Section 4.

The authors of this paper have individually and collectively analysed the challenge relationships, evaluating how the different challenges are influencing each other, and ranking the cells of the diagram consequently through scores. 3 for strong influence of one challenge onto another, 2 for medium, 1 for weak and 0 for none. The outcome of this internal consultation is reported below.

Results

The combined N2 diagram, including the prioritisation provided by the writing group, is shown in Figure 6 where the diagram is colour-coded by averaging the scores provided in the consultation.



Affecting Challenges \ Affected Challenges	System Evolution	Increasing Complexity	Design for Resilience	Resilience Perfomance Tensioning	How Affecting
System Evolution		0.67	0.5	0.67	0.61
Increasing Complexity	0.92		0.92	0.33	0.72
Design for Resilience	0.67	0.33		0.42	0.47
Resilience Perfomance Tensioning	0.92	0.42	0.83		0.72
How Affected	0.83	0.47	0.75	0.47	

Figure 6 Combined N2 diagram. The challenges running down the columns are affected by the challenges running along the rows.

Interpretation of the N2 diagram

The diagram shows that:

- **SE and DFR are greatly influenced by the other three**. This means that when researching system evolution, all other challenges have to be investigated at the same time. The same applies for design for resilience. Of the two, **SE is the most susceptible** to the outcomes of the investigation carried out in all the other challenges.
- Conversely, increasing complexity and resilience–performance tensioning does not seem to be affected by the other challenges, in comparison to the other two. This would suggest that **IC and RPT can be investigated ahead of addressing SE and DFR**. Their scores are quite similar, both along the rows and the columns, this does not suggest any particular prioritization between these two.
- **SE is the most affecting and affected challenge**, which supports the common sense observation that any of the other challenges have to consider the state of the system in time, both in terms of design (acting on the system) and in terms of analysis (the system transformations will change the way of approaching the other challenges.

Research Questions and Prioritisation

The N2 diagram highlights the dependencies between the four challenges and can be used to inform the prioritisation of the research. It is advisable to prioritise the challenges less affected by the unknowns contained in the others. In this sense, the first challenge to be addressed is Increasing Complexity. The research should start addressing the questions in Section 4, which mainly concern the introduction of cyber systems to work along the physical systems or retrofitting these with a cyber counterpart.

A parallel stream exploring performance-resilience tensioning can also be initiated, as the dependency on increasing evolution would appear to be limited. Performance-resilience tensioning is intrinsically linked to the whole system optimisation as opposed to the optimisation of subsystems. Introducing a measure of resilience that refers to the design is fundamental to quantify and attribute a value to the resilience on pair with other performance indices.

As the impact of designing for resilience on system evolution is larger than its reciprocal, design for resilience is the first of these two to be addressed. However, as they are both heavily affected by PRT and IC, it is advisable to undertake the research in how to design for resilience only at a later stage. DFR should ideally leverage the new knowledge acquired investigating PRT.

Finally, the questions about System Evolution should be addressed. This is coherent with the essence of complex systems, which are characterised by adaptive and time variant behaviours. This challenge should leverage the new knowledge acquired when investigating the issues of increasing complexity as it primarily considers engineering systems as interventions in legacy systems. The theme of systems under different authorities might logically target the growing complexity of the policy environment as it strives to capture the increasing complexity of our engineering systems.

The Next Steps

The future strategic research agenda for resilience of complex engineering and engineered systems needs to start from the assumption that society is supported by increasingly complex engineered systems, for which resilience should be defined as an integral component of system performance. In particular we can draw the following conclusions about the priorities for the strategic research agenda:

- Research in the resilience of complex engineered systems should start with the increasing complexity of society and the systems that support it. Phenomena resulting from bolting new systems onto legacy substrates should have the priority over the evolution of the systems, the direct investigation into ways to deliver resilient design, and the balance between resilience and performance.
- Work to understand the balance between resilience and performance present in complex engineered systems that defines the design of our complex engineered systems should be undertaken before investigating how to design for resilience.
- Understanding the system evolution under the internal (emergent) and external pressures is enabled by acquiring the ability to design for resilience.
- Our ability to design for resilience will be in turn the product of a better understanding of our systems, their degree of complexity, their evolution the pressures that drive more or less resilient designs. As such the challenge of designing for resilience can only be tackled by building upon the knowledge acquired by research in the other three. In particular it has to proceed in parallel with a renewed, complexity-science-enabled understanding of the system evolution.

These final considerations are the basis to develop the strategic research agenda for the grand challenge of risk and resilience in complex engineering (and engineered as we have argued) systems. This strategic research agenda will be the next and final endeavour of the ENCORE Network+.

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APPENDIX 1 - GLOSSARY

System	An assembly of components, interconnected in an organized way to form a whole, exhibiting properties as a whole, distinct from the (combined) properties of its components.
Component	A part of a system – which may itself be a system in its own right, a sub-system or an “atomic” element. From the point of view of the system being considered any of these is a “component” of the system
Complex	A problem or solution having many inter-related aspects or components to consider, each of which has its own (at least partly) autonomous or independent behaviour, influenced by interactions with other elements. Typically, the components have independent life-cycles, are not subject to a common authority, and may be able to operate as purposeful systems separate from the complex system
Complicated	A problem or solution having many aspects or components to consider, but nonetheless amenable to rational planning, design and execution, albeit, perhaps, on a large scale
Complexity	The quality or condition of being complex (see above)
Engineering [System]	The methods, processes and resources needed to create and sustain a technical solution that meets the requirements of the stakeholders
Engineered [System]	The set of components that collectively perform the function(s) stipulated in the solution to specified problem requirements. The Engineered System is the outcome of Engineering activity
Emergence	The phenomenon whereby the properties or behaviours of a (whole) system may be unlike those of its components. Such differences can be expected or unexpected; and desired or unwanted. In a Complex System, the nature, occurrence and magnitude of emergent properties or behaviours may not be predictable in terms of those of its components
Complexity Theory	No such single thing; numerous variants depending on the domain in which complexity is being considered – e.g. computational, social, organisational, abstract automata, ...
Complexity Science	The scientific study of complex systems, systems with many parts that interact to produce global behaviour that cannot easily be explained in terms of interactions between the individual constituent elements
Resilient	Able to prepare, mitigate, adapt to, and/or rapidly recover from the effects of potentially “disruptive” events
Robust	Able to resist the effects of potentially “disruptive” events or of change in the system environment
Fragile	Becomes more sensitive to potentially “disruptive” events after repeated occurrence (“concave” sensitivity)
Brittle	Able to resist exposure to stress only to a threshold level, beyond which resistance decreases rapidly

APPENDIX 2 - DEFINITION OF GROUPS IN CONTEXT OF ENCORE

The **Research Community** has the task to deliver the outputs in line with the government priorities and in a way industry can make use of them in the development of CES. It has moreover the task to identify priorities for areas of research and scope of what should be developed in conjunction with industry. This technical note is an example of how to achieve this.

Industry influence the Government's agenda by defining the desirable outcomes as performance for CES in terms of resilience. Industry currently needs to fill the knowledge gap to be able to create resilient complex engineered systems and to derive value from them. It also needs to challenge its top-down approach, which is effective for complicated systems, and consider a bottom up approach, leveraging collaboration with the research community. This needs to go beyond the engineering aspects.

Public companies and Regulated industries, for example private providers operating with limited competition (e.g. supply of water, electricity and rail transport), or arm's length management companies owned by government (some public housing, rail infrastructure). These are typically heavily regulated environments in which bringing about change and providing incentives for investment has challenges.

Government includes regulators and research funders. This group defines the areas of interest through research calls and setting requirements based on policy consideration. Government needs advice from the research community about the exploitation of the research and its support for further research into resilience. In this context, the ENCORE project created the opportunity to work towards the networking for the new research leaders, currently in their early academic career.

Educators and Trainers represent the groups who are responsible for developing qualifications and delivering training in further education, whether full or part time. They have an increased role with the expansion of funding sources, partly supported by levies, which have the potential to build a stronger relationship with industry.

People as users of the services supported by CES they have requirements and expectations of service levels and value for money. This encapsulates for example cost, environmental impact (local and global), social need, availability. By generating demand, people help drive the Government agenda and hence the research. Resilience of services impact people and while they are unlikely to objectively determine the degree of resilience required, this can be assessed and become another factor in designing CES and influencing policy by Government.

ENCORE is the EPSRC funded Network+ gathering the communities of academics, professionals, and practitioners in the areas of Complexity, Engineering and Resilience to set the research agenda that will guide the efforts, nationwide, towards more resilient Complex Engineering Systems (CES).

ENCORE Network+ addresses the Grand Challenge area of Risk and Resilience in Complex Engineering Systems.

CES examples include complex products consisting of many interacting components such as gas turbine engines and complex networks such as the UK's digital, energy and transport networks.

We lack a coherent understanding of what unifies the complexity of entities such as jet engines, cities and our national infrastructure, and of what tools we need necessary to manage and build CES that exhibit resilience or quantify the risks inherent in such systems.

We shall exploit and synthesise our knowledge of natural and engineered systems, our current theories of complexity and the quantification and management of uncertainty and advanced optimisation techniques in order to develop powerful new tools and new understanding.

encorecomplexity.org
encore@sheffield.ac.uk
🐦 @encore_network