Lloyd's Register Foundation

Foresight review of resilience engineering

Designing for the expected and unexpected

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About the Lloyd's Register Foundation

Our vision

Our vision is to be known worldwide as a leading supporter of engineering-related research, training and education, which makes a real difference in improving the safety of the critical infrastructure on which modern society relies. In support of this, we promote scientific excellence and act as a catalyst working with others to achieve maximum impact.

The Lloyd's Register Foundation charitable mission

- To secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air.
- The advancement of public education including within the transportation industries and any other engineering and technological disciplines.

About the Lloyd's Register Foundation Report Series

The aim of this Report Series is to openly disseminate information about the work that is being supported by the Lloyd's Register Foundation. It is hoped that these reports will provide insights for the research community and also inform wider debate in society about the engineering safety-related challenges being investigated by the Foundation.

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Executive summary

This report explores how resilience engineering could enhance the safety of life and property through the improved resilience of engineered structures, systems, organisations and communities around the world. Its findings were developed through a workshop followed by an open consultation process. Lloyd's Register Foundation will use this review to identify aspects of resilience engineering that align with its charitable objectives and where the Foundation might focus its research and other grant giving to make a distinctive positive societal impact.

Resilience describes the emergent property or attributes that some systems have which allows them to withstand, respond and/or adapt to a vast range of disruptive events by preserving and even enhancing critical functionality. The term is used widely over many different fields of study, but quantitative metrics of the resilience of socio-technical systems are not well established and standards and processes are still emerging. Rigorous methodologies and technical integrity is needed to support the uptake and impact of resilience engineering.

Resilience can be built by developing capabilities to monitor, respond, anticipate and learn. Challenges to resilience include 'external' threats from a range of hazards including environmental, social, economic and technological changes, and 'internal' threats from organisational deficiencies. New technologies can provide opportunities but also threats to resilience.

Globalisation, uncertainty, demographic change and an excessive focus by managers around current status are identified as challenges to resilience. A lack of incentives, capacity, education and training programmes, effective communication, and parameters to characterise resilience, are also identified.

Engineered solutions to improved resilience of socio-technical systems will require a trans-disciplinary approach including engineering; the natural, physical, and social sciences; economics; and policy. Solutions will require assessment and predictive capabilities that do not presently exist, including identification, collection and analysis of relevant data. Pro-active approaches such as 'Safety 2' and performance-based engineering can support the resilience goal of preserving critical system functionality in the face of anticipated and unanticipated conditions. The report also identifies the serious challenge of retrofitting existing systems.

There are a wide range of possible actions and interventions that could support resilience. These range from developing facilities and tools to supporting new knowledge and technologies; fostering international collaboration and understanding of global systems; establishing foundational research; learning from ecology and ecosystems; and developing better incentives for improving resilience.

This report explores how resilience engineering could enhance the safety of life and property around the world

The Foundation is uniquely positioned to play a leading role in an international effort to better understand, communicate and improve resilience towards safety of life and property. It should invest in resilience engineering, with the aims of maximising benefit to society while also leveraging, and not duplicating, activities underway elsewhere.

The Foundation can bring a substantial societal benefit by building the resilience of critical infrastructure sectors. This is the primary recommendation of this review. Society depends on the proper functioning of essential services such as food and water, energy, transportation, telecommunications, the built environment and healthcare. These sectors are increasingly complex and interdependent, acting at a global scale, and making them susceptible to catastrophic and cascading failure under stress. The Foundation can build resilience, for example, through a programme addressing:

- governance: incentives, standards and rules
- capacity building and engagement: professional development, publications, communication and public engagement
- data and supporting tools: shared datasets, modelling and simulation, decision support
- international and global scale networks: studies of global systems, supply chains, knowledge networks.

In implementing this recommendation, the Foundation should also work with others to ensure mutual sharing of knowledge, skills, tools and networks between critical infrastructure sectors and other application domains, for example, organisations working to build resilience in cities, in countries and in businesses.

Finally, in implementing the primary recommendation, the Foundation should work with the wider scientific community and in partnership with other funders to secure the fundamental understanding, technical underpinnings and skills base needed for resilient critical infrastructures, and help to mature the discipline of resilience engineering.

Foreword

Lloyd's Register (LR) was established in 1760, and became one of the earliest global businesses, but in the 255 years since it was set up the world has become an entirely different place. The first ships classified by LR were sailing ships constructed from wood, but ships today are designed, constructed and operated in a way and on a scale that was unimaginable then. Social, economic, political, environmental and technological conditions have all changed. Sometimes these changes come as short term shocks and sometimes they are more predictable over a longer time scale. All these changes have shaped the way LR does business today and they will inform the way LR, and the sectors it serves, do business tomorrow. But what is it that causes some businesses to survive change where others do not? Why do some countries and cities thrive under change while others struggle? How do some engineered structures and systems withstand adverse conditions while others collapse catastrophically? The answers lie in the consideration of resilience.

The Lloyd's Register Foundation is a charity that supports safety of life and property, and public education. When catastrophic failure occurs, lives can be lost and damage may be unrecoverable. This is why the Foundation has chosen resilience engineering as one of its research priorities. How can we build systems, infrastructures, networks, organisations and the associated human and social capacity to withstand stress and shock? How do we make catastrophic failure less likely when we do not always know what the risks are?

The characteristics of the modern world mean these questions are more urgent than ever. Communications, financial systems and critical supply chains are highly networked and interdependent. Demographic change is unprecedented and human capacity more mobile than ever. Global companies can have more influence and impact on lives than governments. Globalisation allows shocks to rapidly propagate across international boundaries. Highly networked systems and societies are not well understood, and unexpected characteristics and features may emerge. In parallel to this, rapid technological change can provide both opportunities and threats to resilience. How do we best use technology to improve safety and where does it present a threat?

In this report we set out the challenge for resilience engineering. We consider what others are doing in this field and what actions the Foundation might take to support and promote resilience. In doing this our aim is to improve the safety of the critical infrastructure on which modern society depends. We do this because life matters.

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The Tomb of Cyrus, built in the 4th century BC, is said to be the oldest base-isolated structure in the world. Base isolation, also known as seismic base isolation, is one of the most popular means of protecting a structure against earthquake forces.

Background

This report, commissioned by the Lloyd's Register Foundation, explores the emerging field of resilience engineering. How can resilience engineering enhance the safety of life and property and better assure the continuity of critical functions, through the improved resilience of engineered structures and systems, organisations and communities around the world?

The Foundation has identified resilience engineering as a strategic funding priority[1] for its research grant giving. Building on the findings of this review, the Foundation will look to identify aspects of resilience engineering that provide opportunities and align with its charitable objectives and where the Foundation might focus its research and other grant giving to make a distinctive positive impact.

A workshop was held on 15-17 April 2015 hosted by Stevens Institute of Technology with the aim of identifying the applications of resilience engineering to sectors of relevance to the Foundation and the gaps in our ability to understand, communicate and improve resilience in these sectors. The workshop brought together professionals from more than a dozen countries

[1] Lloyd's Register Foundation Strategy 2014–2020 www.lrfoundation.org.uk/Images/46949-.pdf

and five continents to share perspectives on the emerging field of resilience engineering, and to explore how the Foundation might make a distinctive contribution to the field. Experts came from a wide range of infrastructure sectors including healthcare, energy, transport, food and water, and IT and communications, bringing perspectives from industry, from government, from city and regional-scale planning, and from academia.

How can resilience engineering enhance the safety of life and property and better assure the continuity of critical functions

The participants considered the following questions:

- What is resilience engineering?
- What are the impacts, trends, and opportunities?
- What are the gaps in knowledge?
- What funding interventions will make the biggest impact to support the Foundation in delivering its charitable aims?
- Who else is interested and who should we work with?

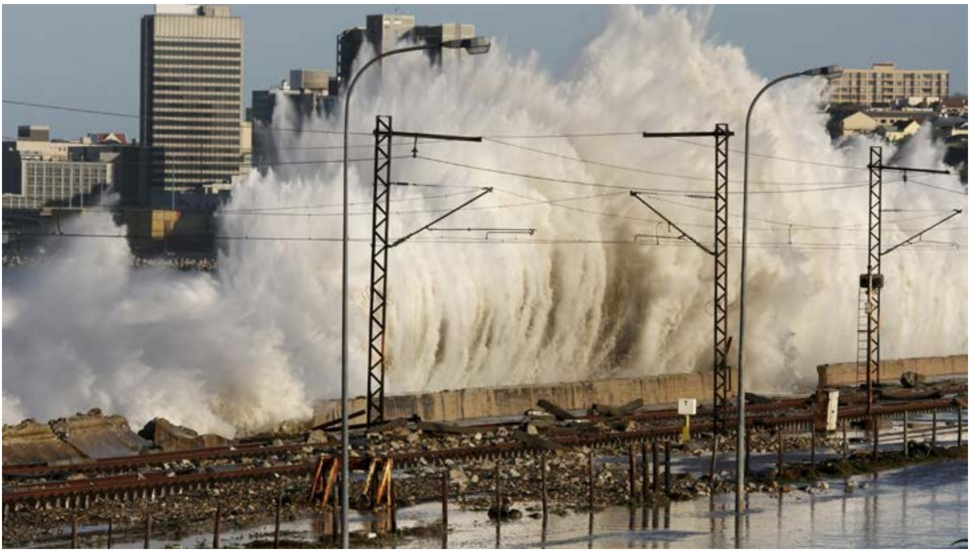
This report builds on the workshop findings and an open consultation. Contributors to the April 2015 workshop and the open consultation are listed in Appendix 1.

The Lloyd's Register Foundation is a charity and owner of the Lloyd's Register Group Limited (LR). LR is a 255-year old organisation providing independent assurance and expert advice to companies operating high-risk, capitally intensive assets in the energy and marine sectors. It also serves a wide range of sectors with distributed assets and complex supply chains such as the food, healthcare, automotive and manufacturing sectors.

What is resilience engineering?

The term resilience has been in use for many years by a variety of disciplines. It describes the emergent property, or attribute, that some systems have which allows them to **withstand, respond and/or adapt to a vast range of disruptive events.** These systems include ecological systems[2]; physical systems (for example, structures designed against earthquake loading); complex systems (for example, supply chains with enhanced resilience); and human communities (for example, cities made resilient to flooding). Natural and man-made disruptions around the globe have, over the last decade, spurred widespread interest in the improvement of resilience.

Norris et. al.[3] provide a useful summary of the applications of the term 'resilience' over the last 40 years. They conclude that in the context of human communities, organisations and societies,



[2] Holling, CS. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics. Vol. 4: 1-23.

[3] Norris, FH; Stevens, SP: Pfefferbaum, B; Wyche, KF; Pfefferbaum, RL. 2008. Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. Am J Community Psychol. 41:127–150.

resilience can best be defined as "a process linking a set of adaptive capacities to a positive trajectory of functioning and adaptation after a disturbance".

The definition of resilience adopted by the Rockefeller Foundation's 100 Resilient Cities initiative is "the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt, and grow no matter what kinds of chronic stresses and acute shocks they experience". The term 'grow' captures the importance of including the elements of innovation, improvement and wellness to the definition of resilience. The Rockefeller Foundation's specific mention of two basic types of disruptions, short-term acute shocks and longer-term chronic stresses, is also of note.

Some authorities, recognising the value of resilience approaches, are developing standards, guidelines and processes to support improved resilience. These include:

- British Standards Institution: Guidance on organisational resilience[4]: "Organisational resilience is the ability of an organisation to anticipate, prepare for and respond and adapt to everything from minor everyday events to acute shocks and chronic or incremental changes. Resilience is a relative, dynamic concept."
- US President Policy Directive 21 - Critical Infrastructure Security and Resilience[5]: "The term resilience refers to the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."
- The United Nations (UN) defines resilience as: "… ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions"[6]. The UN Office for Disaster Risk Reduction (UNISDR) began in March 2015 to implement a new ISO standard for resilient and sustainable cities, ISO 37120[7].

[4] BS 65000:2014: Guidance on organisational resilience, British Standards Institution, 2014
[5] www.whitehouse.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil
[6] United Nations Office for Disaster Risk Reduction (UNISDR). 2009. 2009 UNISDR Terminology on disaster risk reduction, UNISDR: Geneva.
[7] www.iso.org/iso/37120_briefing_note.pdf

Some common themes across these definitions have emerged, including:

- the presence or emergence of a threat or event that disrupts normal or expected function
- a system coping with that event and trying to maintain or achieve some desired function
- the mechanisms for coping with the event generally include anticipation/preparation, absorbing/ withstanding the effects of the event, adapting to maintain some level of functionality during the event, and recovering to achieve an ultimate, desired level of functionality.

These common themes provide a starting point around which the emerging field of resilience engineering can begin to make advances, for example, through the development of metrics and design principles. The word 'engineering' infers the application of science to create products and processes to enhance resilience. Perhaps as a result of the various definitions of resilience, and the difficulty of measuring it as an outcome, most of the published work to date in resilience has been qualitative. Common language, underlying theory and quantitative rigour is needed to support its study, particularly when describing the stochastic nature of resilience along a time domain. A common feature of engineered systems and living systems is that they are inherently interconnected. However, often their interdependencies and shared vulnerabilities are not well understood. As stated by Woods[8], "the future is intensely technological and intensely human". Therefore, to improve resiliency the study and application of resilience engineering must be trans-disciplinary and must build on expertise across multiple sectors and jurisdictions.

So how do we increase resilience? Borrowing from lessons learned in a number of areas[9] the following are suggested:

- The ability to **monitor.** Monitoring supports preparedness. It includes knowing what to look for and being able to monitor what could positively or negatively affect the system's performance. Monitoring should cover the system's own performance as well as what happens in the environment.

- The ability to **respond.** Knowing what to do, or being able to respond to regular and irregular changes, disturbances, and opportunities by activating prepared actions or by adjusting current modes of functioning to prevent significant mal-effects.

- The ability to **learn.** Knowing what has happened, or being able to learn and adapt from experience, in particular to learn the right lessons from experiences.

[8] Woods, D. 2015. Presentation at the Sixth Symposium of the Resilience Engineering Association, Lisbon, Portugal, June, 2015.

[9] Hollnagel, E; Pariès; Woods; Wreathall (eds). 2006. Resilience engineering in practice (Ashgate Studies in Resilience Engineering), ISBN 978-1-4094-1035-5.

Weather monitoring in a shipping control room

- The ability to **anticipate.** Knowing what to expect, or being able to anticipate developments further into the future, such as potential disruptions, novel demands or constraints, new opportunities or changing operating conditions.

For engineered systems, Hollnagel[10] suggests "a system is resilient if it can adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions". Linkov et. al.[11] conclude that planning must begin with an assessment of "the probability that the system will reach the lowest point of the critical functionality profile". This point of critical functionality must then be planned for, but in resilience terms this does not necessarily mean returning to the original socio-technical configuration. **What matters is preserving and even enhancing critical functionality, not the pre-existing system.**

[10] http://erikhollnagel.com/ideas/resilience-engineering.html
[11] Linkov I; Bridges, T; Creutzig, F; Decker, J; Fox-Lent, C; Kröger, W; Lambert, JH; Levermann, A; Montreuil, B; Nathwani, J; Nyer, R; Renn, O; Scharte, B; Scheffler, A; Schreurs, M; Thomas Thiel-Clemen, T. 2014. Changing the resilience paradigm, Nature Climate Change 4, 407–409.

To use an example from the water sector, a disaster that significantly compromises an existing drinking water system might not be met, in the longer term, with a like-for-like asset replacement. Instead system operators may elect to substitute compromised assets (which may have been established in a much earlier era) with new socio-technical systems able to deliver critical functionalities differently (for example, smaller spatial footprint, cheaper, less carbon-generative, etc). Mutchek and Williams[12] suggest that this sort of resilience should lie at the heart of emerging 'smart grids' or 'smart cities'. Achieving this 'resilience by design', where the system function, and not the system itself, is preserved or even enhanced, lies at the heart of resilience engineering.

Finally, in taking the field of resilience engineering forward we should think of resilience as a property that exists on a continuous spectrum, rather than as a binary state. When we do this our goal changes from 'engineering a resilient system' to 'engineering a more resilient system'. This helps the development of metrics, design principles, standards, etc[13]. This is more useful than suggesting the concept of 'a resilient system' as a binary state , in other words, that a system is either resilient or not.

[12] Mutchek, M; Williams, E. 2014. Moving towards sustainable and resilient smart water grids. Challenges 2014, 5, 123-137.
[13] Vugrin, E. Personal communication

Examples of resilience engineering applications, standards, guidance and policies

The US Department of Homeland Security's (DHS) STAR™ Home Pilot Project

DHS is undertaking a pilot project to promote building design that recognises best practices which help make buildings more resilient. Through the pilot project, DHS will work together with the private sector, to engage homeowners, builders and contractors in communities at high risk for certain natural disasters, to identify proactive steps to enhance the resilience of the homes. The project will allow the private sector to identify and designate residential homes that are voluntarily built or remodelled to employ design features that are both affordable and proven to enhance resilience to disasters. The Resilience STAR™ designation will be given to structures that are built to withstand damage from certain disasters, using the standards and third-party verification process in the Insurance Institute for Business & Home Safety's (IBHS) FORTIFIED programmes. The FORTIFIED standards are designed to improve the quality of residential construction and feature practical, meaningful solutions for new and existing homes throughout the US[14].

The US Federal Emergency Management Agency's Private Sector Preparedness (PS-PREP) programme

In 2007, Congress directed DHS to establish and implement the voluntary private sector preparedness accreditation and certification programme. The result of this directive, PS-Prep™, is designed to improve the preparedness of private sector and non-profit organisations through conformance to consensus-based preparedness standards and best practices. PS-Prep™ enables organisations to identify and implement the necessary steps for instituting and maintaining a comprehensive management system that addresses business continuity, organisational resilience, emergency and disaster management. In addition, DHS will provide recognition for those entities that certify to the adopted preparedness standards. PS-Prep™ is a voluntary programme, primarily serving as a resource for private and non-profit entities interested in instituting a comprehensive business continuity management system[15].

[14] www.dhs.gov/blog/2013/11/18/engineering-resilience-resilience-star%E2%84%A2-home-pilot-project

[15] www.fema.gov/about-ps-preptm

A White Paper on Resilience Engineering for Air Traffic Management

In January 2007, EUROCONTROL launched a project aiming to understand the new area of resilience engineering and its relevance to air traffic management (ATM). Resilience engineering is developing important tools and methods for both system developers and people responsible for the maintenance and management of system safety, in a number of industries. European Organisation for the Safety of Air Navigation (EUROCONTROL). September 2009.

The Resilient Enterprise (MIT Press), Sheffi, Y. 2005

This book provides several examples of businesses that have employed resilient design practices within their business operations. For example, Intel has the Copy Exactly! programme that builds each of its semiconductor fabrication facilities to the same specifications, creating interchangeable processes and facilities. During the SARS outbreak in Asia, Intel knew that if its employee population or infrastructure was affected, it could move production to other global locations with no impact to production levels.

- Resilience is a term common to many fields of study. Resilience helps systems to withstand, respond and/or adapt to a vast range of disruptive events by preserving and even enhancing critical functionality.

- Quantitative metrics of the resilience of socio-technical systems are not well established. Standards and processes are emerging.

- Rigorous methodologies and technical integrity is needed to support the uptake and impact of resilience engineering.

Understanding resilience through case studies

We can gain an understanding of both the challenges to resilience, and the characteristics and benefits of more resilient engineered systems, by examining examples of disruptive events.

Hurricane Sandy in New York City

In October 2012, Hurricane Sandy hit the metro-New York region. Its size and direction of travel resulted in a significant storm surge, more than 3 metres in some areas, along the coast of New Jersey and inside New York Harbor. Throughout the US, more than 650,000 homes were destroyed or seriously damaged, and more than 9 million customers lost electricity. Total direct economic losses due to the hurricane have been estimated as $72 billion[16].

The preparation and response to Hurricane Sandy varied widely across businesses and governments. In the transportation sector, New Jersey Transit suffered major losses of equipment and prolonged periods of service outages because of a lack of preparation to protect equipment from storm surge and flooding damage. By contrast, the New York City subway system took steps that resulted in it being able to restore partial service less than

The devastation left by Hurricane Sandy, in Far Rockaway, Queens, NY, USA

[16] Aon Benfield. 2013. Hurricane Sandy Event Recap Report. 50p.

three days after landfall, and was nearly fully operating in less than a week. The delivery of containerised cargo through the port of New York and New Jersey, representing 61.2% of all such cargo in the North Atlantic in 2012[17], was suspended for more than a week. However, much of the cargo flow was able to still reach the region with minor delays via re-routing to other ports (for example, Halifax) that had excess capacity.

In contrast, there were no effective workarounds for the delivery of urgently needed refined fuels for the New York metropolitan region. The storm disrupted the maritime-based fuel transport systems for several days and damaged major refineries and a primary pipeline carrying fuel from the Gulf Coast. Power outages and inadequate or poorly-sited backup powering systems caused significant disruption to the hospitals in the New York region. There was little understanding or planning for the disruption of critical health services such as providing essential dialysis in settings outside hospitals. In short, Hurricane Sandy revealed that even though several major hurricanes have struck the metro-New York area over the past 150 years and advance warning was given of Hurricane Sandy, lifeline infrastructure sectors were severely compromised due to a lack of investment in mitigation measures and inadequate planning for managing cascading disruptions across interdependent systems.

The 2003 European and North American cascading power blackouts
In 2003, both Europe and North America experienced cascading failures of their power distribution networks, causing widespread disruption. The consequences following the initial loss of the electricity networks were far-reaching due to the nature of the dependencies and interconnections with other vital services and facilities.

The event in North America occurred on 14 August and affected more than 45 million people in Canada and the USA. In some areas, the power was not fully restored for four days. An overload on the grid that distributes electricity to the eastern US caused circuit breakers to trip at generating stations across the region and into Canada. The blackout caused disruptions on the rail and subway services, with passengers needing to be evacuated from tunnels. Airports also experienced serious disruptions, traffic lights went out of sequence, people required rescuing from elevators and there was pressure loss in water distribution systems. The incident led to an increased use of mobile phones, overloading these communications networks.

Just over one month later, a similar incident occurred in Northern Italy and part of Switzerland. A cascading failure of the power distribution network caused a widespread blackout. This

[17] http://www.panynj.gov/port/pdf/2012_trade_statistics_sheet.pdf

affected 56 million people and again impacted transportation services, with 30,000 people stranded on trains, 110 other trains cancelled, and many flights also cancelled. As in North America, people were trapped in underground trains. In this case the interconnectivity of the distribution systems in Italy and Switzerland with those in France, Austria, Slovenia and Croatia resulted in even more severe consequences.

Cyclone Phailin in India

In October 2013, Cyclone Phailin made landfall along the eastern coastline of India, in Orissa and Andhra Pradesh states. The storm affected more than 13 million people, damaged more than 300,000 homes, and caused 44 deaths. The impacts from this potentially devastating storm were significantly reduced because of the preparation and response by emergency management authorities, including early warning, the implementation of evacuation plans (among the largest evacuations in the nation's history), the provision of cyclone shelters, and the training of thousands of first responders. This is noteworthy because in 1999, a super-cyclone killed more than 10,000 people in Orissa state[18].

Cyclone Phailin over the Bay of Bengal on 11 October 2013

[18] http://www.unep.org/pdf/UNEP_GEAS_NOV_2013.pdf

Flooding events in England and Wales

Over the last decade, England and Wales have experienced frequent water-related challenges. The floods of Gloucestershire in 2007 and Somerset in 2014 in particular demonstrated the multi-faceted challenges of ensuring resilience to flooding. The impacts were both local (extensive property damage and three deaths) and more widespread, with national food and transport systems severely impacted. The 2014 event caused major disruptions to road and rail systems, including the severing of the only rail line to the South West of England resulting in rail services to the west being suspended for two months. Gatwick Airport suffered severe disruption on 23 and 24 December, with partial closure of its North Terminal because basement flooding knocked out key power and IT systems[19]. After the Gloucestershire floods in July 2007, the government commissioned a national review (the Pitt Review) of flood preparedness: Learning lessons from the 2007 floods. This wide-ranging review pointed to the need for major changes to infrastructure planning and management, land and development planning, and emergency information and response systems. The word 'resilience' appears no less than 355 times in the 462-page document. The direct legislative result was the Floods and Water Management Act of 2010, which shifted attention away from hardening targets and towards working with nature, including rethinking the role of green infrastructure and the need to rebuild social as well as technical resilience. The response to the 2014 event included a 20-year plan that includes dredging, more permanent pumping sites and a tidal barrier, estimated to cost £100 million[20]. These examples highlight the complex socio-technical nature of such events and systems and the need for trans-disciplinary resilience approaches that include social and political considerations.

The cosmic ray problem

The interaction of high energy cosmic rays with the earth's atmosphere generates cascading showers of electromagnetic and secondary particle radiation. These include a flux of high energy neutrons that are intense enough to cause 'single event effects' in many microelectronic devices both on the ground and on board aircraft. A single event effect is a phenomenon whereby the correct operation of a microelectronic device is disrupted by interaction with a single sub-atomic particle. Such effects range from 'soft' errors, that corrupt memory or change logic function in devices, to 'hard' catastrophic errors that lead to a permanent destructive failure of the electronics.

[19] www.gov.uk/government/uploads/system/uploads/attachment_data/file/335115/transport-resilience-review-web.pdf

[20] Taken from: www.bbc.co.uk/news/uk-england-somerset-26157538

These issues became very real in an in-flight incident during a Qantas aircraft flight from Singapore to Perth on 7 October 2008. Serious flight control issues resulted in about one third of the passengers being injured with a dozen serious injuries which required the aircraft to declare a MAYDAY and divert to the nearest airstrip. The Australian Transport Safety Bureau eliminated all environmental causes other than single event effects for which they did not have enough evidence: "There was insufficient evidence available to determine if an SEE was involved, but the investigation identified SEE as an ongoing risk for airborne equipment."[21] This incident raised awareness of the potential for single event effects to damage safety critical systems on the ground and in the air, resulting in consideration of such effects in system design.

[21] ATSB Transport Safety Report Aviation Occurrence Investigation AO-2008-070; Final Report Dec 2011

Impacts, trends, and opportunities: the challenges to resilience

The challenges to achieving improved resilience, in particular of complex socio-technical systems, include a range of external and internal (organisational) influences:

- **Uncertainty** drives a need for improved predictive ability, as well as the need for adaptability and accepting that some level of uncertainty will always exist.
- **Globalisation** means we need to better understand the risks to global businesses that depend on infrastructure and networks that operate across multiple jurisdictions.
- **The lack of parameters by which to characterise resilience** drives a need to quantitatively describe the resilience of a system, structure or network to enable objective decisions on alternative approaches to increase robustness to disruptive events.
- **The lack of incentives** requires participatory approaches that can identify and nurture a 'commonality of purpose' and lower or eliminate the barriers to investment and experimentation.
- **The lack of capacity,** technical and knowledge-based, particularly in areas of the world where advances in resilience are most needed. This drives a need for more effective transfer of technology and knowledge, as well as the need to establish new and more effective avenues for innovation.
- **The lack of education and training programmes** at all levels, from practitioners and researchers to business leaders, policy makers and the general public. Since by definition resilience engineering must consider events that have not yet occurred, this drives a need for the development of innovative education and training systems to include engaging decision makers in virtual reality and immersive environments.
- **The lack of effective communication,** including in particular the communication of 'the resilience imperative' at all levels within the various stakeholder communities and to general audiences. Consensus-building and co-ordination across all stakeholders is essential for success. This will require a sustained dialogue among scientists, practitioners, decision makers, policy makers, and citizens, and it drives a need for effective information-sharing across organisations and domains. Sometimes this will require methods that can protect privacy and proprietary information.
- **Excessive focus by managers around current status** and on single performance indicators for example 'the bottom line'. Prescriptive adherence to safety methods focused on the avoidance of accidents (Safety 1) rather than the safety and resilience of the whole system (Safety 2) can be a barrier to positive change (figure 1 on page 28). The tension between efficiency and resilience is another challenge.

- **Rapid fluctuations in demand** resulting in pressure on different parts of engineered systems, such as transportation systems, for the movement of people and goods.
- **Changes in population,** including changing demographics (for example, an ageing population) as well as population dynamics (for example, migration from conflict and poverty) result in changes in vulnerability. Responses required include housing, health, and other critical service interventions that challenge the resilience of these systems in urban and remote locations alike.

Table 1, on pages 21-26, provides examples of challenges to resilience in each critical lifeline sector identified during the April 2015 workshop along with potential resilience solutions. These potential solutions represent possible research challenges for consideration. This list is not meant to be exhaustive and a further development could include assigning the potential resilience solutions to short, medium and long-term challenges.

- Present and future challenges include ‘external’ threats from a range of hazards and ‘internal’ threats from organisational deficiencies.
- Potential solution pathways need to be trans-disciplinary, including engineering; the natural, physical, and social sciences; economics; and policy.

Table 1
Challenges to resilience and potential solution paths

Sector - IT and communications		
External drivers	Governance, organisational and system drivers	Potential resilience solutions
• Population growth, mobility and migration • Globalisation • Natural disasters • Climate change • Resource scarcity • Technological innovations • Changing public behaviours and attitudes • Disruption to satellite communications • Power outages • Conflict • Terrorism	• Lack of education • Lack of communication • Lack of incentives • Inequities in system capacity across nations • Security and privacy issues • Ageing infrastructure • Increased reliance on IT systems to underpin critical infrastructures • Localised systems (off the grid) • Complexity associated with public-private partnerships • Tension between management for resilience and management for efficiency	• Effective and secure information sharing • Design for resilience, including retro-fit • Back-up power or off-grid • Localised communications capability, including prioritisation schemes • Resilience standards and codes for emerging technologies • Education, training, public communications • Real-time monitoring systems • Visualisation to support decision-making • Autonomous and self-learning systems • Cyber-physical security improvements

Sector - Healthcare and medicine		
External drivers	**Governance, organisational and system drivers**	**Potential resilience solutions**
• Ageing population • Population growth, mobility and migration • Globalisation • Natural disasters • Climate change • Virulent and contagious disease outbreak • Resource scarcity • Technological innovations • Changing public behaviours and attitudes • Conflict • Terrorism	• Lack of education • Lack of communication • Lack of incentives • Surge capacity degraded by cost-saving efforts to promote system-wide efficiency improvements • Inequities in system capacity across nations • Security and privacy issues • Complexity associated with public-private partnerships • Tension between management for resilience and management for efficiency • Complexity of surge vs everyday capacity	• Effective and secure information sharing • Invest in global surge capacity, enabled by design, and analytical tools • Address health care capacity inequities in developing vs developed nations • Develop better understanding of potential unintended consequences of health care 'solutions', in particular during crises • Develop incentives for resilient design and practices • Enable self-reliance and well-being, eg using social media • Education, training, public communications

Table 1 continued
Challenges to resilience and potential solution paths

Sector - Power and utilities		
External drivers	Governance, organisational and system drivers	Potential resilience solutions
• Population growth, mobility and migration • Globalisation • Natural disasters • Climate change • Resource scarcity • Technological innovations • Changing public behaviours and attitudes • Power outages • Conflict • Terrorism • Heat islands	• Lack of education • Lack of communication • Lack of incentives • Inequities in system capacity across nations • Ageing infrastructure • Localised systems (off the grid) • Complexity associated with public-private partnerships • Reliance on power systems to underpin critical infrastructures • Regulatory structure often does not include resilience • Tension between management for resilience and management for efficiency • Distributed systems	• Critical lifeline systems designed for temporary operation without access to power • Education, training, public communications in terms of short (civil contingency) and longer term resilience • Build a capability to anticipate, assess and adapt to changes (environmental, socio-technical, and geo-political) • Portable systems to adapt to population migration • Incentives for resilient design and retro-fitting • Real-time monitoring • Add resilience to utility performance metrics • Cyber-physical security improvements • De-carbonisation

Sector - Transportation and shipping		
External drivers	**Governance, organisational and system drivers**	**Potential resilience solutions**
• Population growth, mobility and migration, and the associated changes in flows of people and cargo • Globalisation • Natural disasters • Climate change • Resource scarcity • Technological innovations • Changing public behaviours and attitudes • Conflict • Terrorism	• Lack of education • Lack of communication • Lack of incentives • Inequities in system capacity across nations • Ageing infrastructure • Tension between management for resilience and management for efficiency	• Regulations and policies that can keep up with technology changes • Big data solutions, using sensors, modelling and simulation • Incentives for resilient designs and retro-fitting • Autonomous systems that incorporate resilience • Supply chain security via non-intrusive inspection • Develop better understanding of interconnections • Education, training, public communications

Table 1 continued
Challenges to resilience and potential solution paths

Sector - Food and water		
External drivers	Governance, organisational and system drivers	Potential resilience solutions
• Population growth, mobility and migration • Globalisation • Natural disasters • Climate change • Resource scarcity • Technological innovations • Changing public behaviours and attitudes • Power outages • Conflict • Terrorism • Environmental disaster, eg chemical spill • Virulent and contagious disease outbreak	• Lack of education • Lack of communication • Lack of incentives • Inequities in system capacity across nations • Ageing infrastructure • Sanitation • Complexity associated with public-private partnerships • Tension between management for resilience and management for efficiency	• Incentivise the distribution systems to address inequalities • Improve communications and notification mechanisms in inter-linked systems • Education, training, public communications • Low-energy desalinisation • Enhanced food preservation • Reduction of wasteful water use and use of technology to improve water efficiency in agriculture • Behaviour change • Local production and distribution eg ‘urban farms’

Sector - Built environment, including managed land and marine areas		
External drivers	**Governance, organisational and system drivers**	**Potential resilience solutions**
• Population growth, mobility and migration • Globalisation • Natural disasters • Climate change • Resource scarcity • Technological innovations • Changing public behaviours and attitudes • Power outages • Conflict • Terrorism • Heat islands	• Lack of education • Lack of communication • Lack of incentives • Inequities in system capacity across nations • Ageing infrastructure • Rapid growth of 'green' and 'blue' infrastructure • Socio-technical vulnerability • Inadequate capacity of local governments • Complexity associated with public-private partnerships • Megacities • Tension between management for resilience and management for efficiency	• Performance-based building codes, planning for resilience • Incentives for resilient designs and retro-fitting • Proper balance among grey, blue, and green infrastructure • Education, training, public communications • Public participation

Impacts, trends, and opportunities: toward engineered solutions

So far this report has been broad-based, addressing the challenges and activities associated with improving the resilience of communities, infrastructure, and complex networks. Given its mission "to secure for the benefit of the community high technical standards of design, manufacture, construction, maintenance, operation and performance for the purpose of enhancing the safety of life and property at sea, on land and in the air", the Foundation clearly has a strong interest in understanding, communicating and improving the resilience of engineered systems. Engineered systems are often, in reality, components of complex, interconnected, interdependent and frequently international, socio-technical systems. As such, the development of improved understanding and strategies towards more resilient engineered systems must account for all contributing and impacted components, with consideration given to the natural, social, human, built and financial components. It is through this lens of complex socio-technical systems that we must view the challenges and opportunities that lie ahead in improving the resilience of engineered systems.

Taken on their own, each element of an engineered system, in any sector, can be assessed for resilience by examining failures caused by events that exceed the design conditions, for example, by using physical or computational simulations. This approach is clearly inadequate when treating complex engineered systems, many of which exhibit properties that were unforeseen at the time of their design, and all of which can experience failure through combinations of natural and technological factors and social phenomena. The engineered system cannot be isolated from the context of the larger socio-technical system in which it resides. This presents a fundamental challenge to any attempt at assessing resilience to the range of possible disruptions, known and unknown. To produce such a step change in our understanding, and our modelling and assessment capability, would require the sort of advances as those achieved in system risk assessment in the 1960s and early 1970s. The development of the supporting technologies and techniques for the systematic identification of vulnerabilities to natural and man-made events would be required. A significant challenge would then be to establish a quantification process for the associated network resilience and risk. If such a capability could be developed, the exploration of potential design modifications, upgrades and retrofitted solutions required to formulate a more resilient system could be objectively achieved.

In parallel with the development of the predictive and assessment capabilities for complex engineered system resilience, there is a need to establish and collect the necessary data. Because of the large range of network structures on which society depends and the diverse range of threats that must be considered, the data requirement will be context specific. There is great potential for the use of a network observatory in which performance data, operation data and associated costs are collected and analysed in real time giving the whole framework a dynamic capability. This would place a demand on advances achieved through big data initiatives.

The discussion of risk should emphasise the opportunities for investment, and our work should ultimately be less about minimising the risk of failure and more about creating systems that are higher performing under both 'normal' and unanticipated conditions. This is the transition from 'Safety 1', which addresses risk via prevention, elimination and constraints, and toward 'Safety 2', which aims for the capability to succeed under varying conditions, via support, augmentation and facilitation. Many adverse events cannot be attributed to a breakdown of components and so for maximum effectiveness, we need to understand how a system succeeds, not how it fails[22]. In this sense, disruptive events are an opportunity to learn and to improve system performance (see Figure 1).

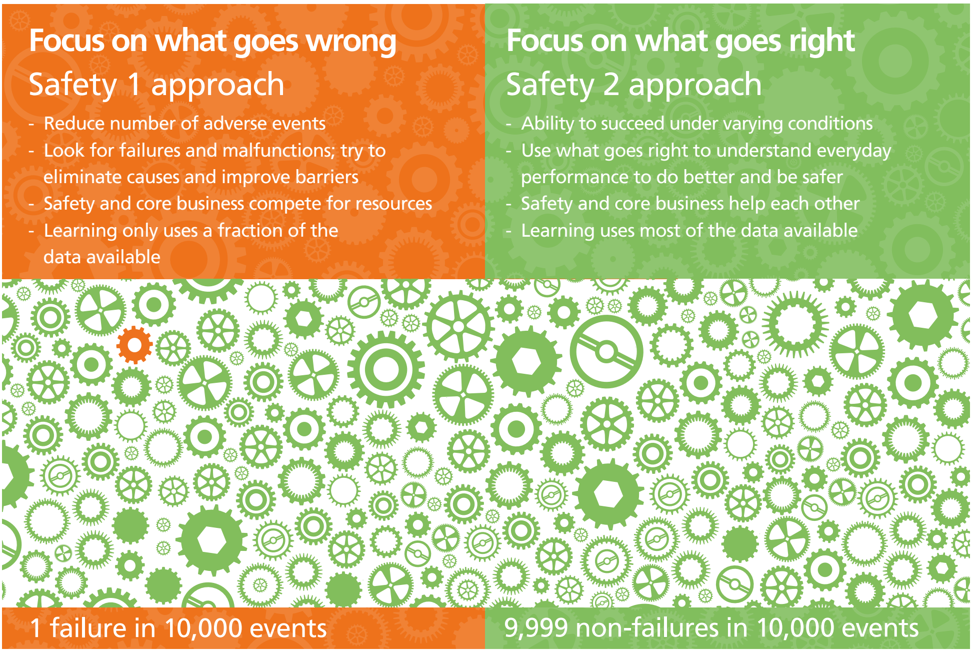


Figure 1: Safety 1 vs Safety 2 approach (after Hollnagel[23])

[22] Hollnagel, E. 2015. Presentation at the Sixth Symposium of the Resilience Engineering Association, Lisbon, Portugal, June, 2015.

[23] Hollnagel, E. 2013. Seminar on human performance in railways. Safety-I and Safety-II: The past and future of safety management.

This approach to an improved resilience of engineered systems is embodied in 'performance-based engineering', which addresses performance primarily at the system level in terms of risk of collapse, fatalities, repair costs and post-event loss of function. The objective of the methodology is to estimate the frequency with which a particular performance metric will exceed various levels for a given design at a given location. These can be used to create probability distributions of the performance measures during any planning period of interest. From the frequency and probability distributions, simple point performance metrics can be extracted that are meaningful to facility stakeholders, such as an upper-bound economic loss during the owner-investor's planning period (Porter[24]). We stress that we have, in this report, advocated that when dealing with complex engineered systems and the extended socio-technical systems, the focus must be on preserving critical functionality and not the pre-existing system.

This discussion would be incomplete without addressing the important challenge of managing ageing infrastructure. For example, Eidinger and Davis[25], in a case study on water system pipelines, highlight that it is impractical for both financial and technical reasons to upgrade all ageing parts of a water system to withstand all levels of future earthquakes (or other hazards) with no damage. The cost to replace or upgrade all pipes and facilities to be seismically rugged is very high. A pragmatic approach (somewhat reflective of a Safety 1 approach) would be to identify and prioritise those facilities most prone to suffering damage that would result in an unacceptable level of service and/or life safety hazard as a result of an event. For other facilities a certain level of damage would need to be expected and so adequate spare parts, personnel and other resources could be made readily available to rapidly repair the damage after the emergency. Another approach would be to carefully assess the critical assets within the system, with the aim of classifying each by their ability to contribute to increased overall system resilience or the required investment to do so.

One final note before we leave this section of the report: we have stressed that engineered systems are often components of complex socio-technical systems. Often, when these systems fail, a first line of inquiry is to search for the causal factors, usually including human error. However the experience of many actual large-scale disruptions, is that human actions were actually responsible for the continuation or restoration of system functioning. A recent dramatic example was the Fukishima nuclear accident. The actions of the power plant employees demonstrated that often in such disruptive events, "people are the resource

[24] Porter, KA. 2003. An overview of PEER's performance-based earthquake engineering methodology. Ninth International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP9), San Francisco, July 6-9.

[25] Eidinger, J; Davis, CA. 2012. Recent earthquakes: Implications for U.S. water utilities. Report: Water Research Foundation, Denver, Colorado, USA.

Wooden 12-foot pipeline diverting water from the North Umpqua River, USA, to a powerhouse

for flexibility and resilience"[26]. The design, construction, maintenance, and operation of engineered systems should be approached with this in mind, perhaps even adopting the 'user centric' approach to design employed by hi-tech companies over the last decade or so. This approach is consistent with the link made throughout this report between resilience engineering and human factors. There is a large body of work that can be drawn on around organisational culture and its impact on system functioning in the face of potential disruption.

- Engineered solutions to improved resilience of socio-technical systems will require a trans-disciplinary approach.
- Solutions will require assessment and predictive capabilities that do not presently exist, including identification, collection and analysis of relevant data.
- Pro-active approaches such as 'Safety 2' and performance-based engineering can support the resilience goal of preserving critical system functionality in the face of anticipated and unanticipated conditions.
- Retrofitting existing systems is a serious challenge.

[26] Yoshizawa. 2015. Presentation at the Sixth Symposium of the Resilience Engineering Association, Lisbon, Portugal, June, 2015.

Supporting the uptake and impact of resilience engineering

This section lays out some example actions and interventions that can support innovation and the understanding and promotion of more resilient engineered systems and socio-technical systems. Many of these suggestions were proposed during the April 2015 workshop.

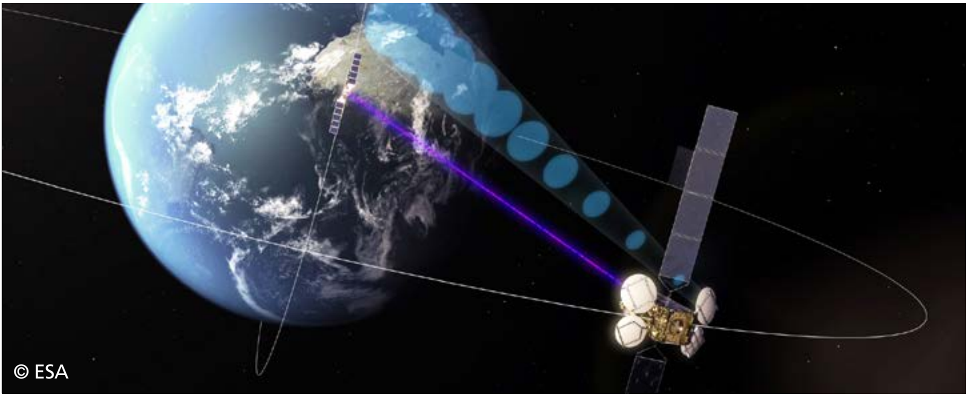
Developing facilities and tools to support new knowledge and new technologies

Establish a global, open, modelling and simulation platform, with the following attributes:

- accepts models of physical phenomena, human behaviour, economic impact, enterprise, financial decision making, structural engineering, climate change, etc, and allows them to interact
- allows for the inclusion of models that are at different levels of maturity
- functions as a testbed for the evaluation of new approaches, the impact of future scenarios, etc
- includes effective visualisation so that it can be used for effective engagement and communication with decision-makers, policy-makers and the general public
- facilitates intellectual exchange among researchers from different disciplines without having all of the researchers in one location
- eventually handles physical and human uncertainty, for example, through ’war-gaming’ and agent-based modelling.

Create a ‘decision exploratorium’ equipped with advanced visualisation (including virtual reality), the ability to generate, display and share ‘what-if’ scenarios, real-time data streams, etc, enabling the discussion of problems that may not normally be discussed openly. Ultimately, this facility or capability could be expanded to a shared global environment, to enable the examination of cultural issues that may affect decision-making.

Develop better communication capabilities and enable information flow between and among systems and sub-systems, down to the individual level. For example, a resilient and safe city will be achieved through improved transparency and trust from better information, communications and monitoring. Better informed individuals make better decisions. The aim is to prepare whole systems to withstand and recuperate from shocks and disturbances at various scales via effective knowledge sharing and faster processing of data. It needs an assigned governance structure to deal with information deficits and improve communications during disturbances in the system.



The European Data Relay System (EDRS) high-speed feeder link relays to Europe. Dubbed the SpaceDataHighway, EDRS will help Earth-observing satellites to transmit large quantities of potentially life-saving data down to Europe in near-real time.

Fostering international collaboration

Establish a global network of researchers and practitioners, with the following attributes:

- clearing house for information
- forum for collaboration in research and education
- vehicle for comparative analysis and best practices
- forum for interaction with government and other authorities and user communities
- vehicle for the development of trust relationships between organisations
- vehicle to attract attention and generate visibility of the imperative of making progress in resilience
- globally-distributed network of researchers that can support the response to disruptions, for example, to gather data
- vehicle for global education, training and public communication.

Facilitate international collaboration via the assembly of a set of case studies of disruptions of various kinds that have had a significant impact on major infrastructure and regional economies, or a set of case studies demonstrating 'what good looks like' (for resilient structures, systems, companies, etc). One vehicle for encouraging strong international and inter-disciplinary collaboration could be the establishment of a summer resilience institute that would gather experts from around the world and across disciplines to work intensively on a set of focused, relevant problems related to resilience.

Develop international continued professional development (CPD) intensive courses. For example courses on urban resilience for local government decision-makers might include case studies from participants, work on 'resilience plans', global urban challenge scenarios, and hands-on solution sets tailored for participants' own cases.

Foundational research

Develop a solid theoretical foundation for the study and engineering of the resilience of socio-technical networks. This would address interconnectedness; modelling the social and technology layers; examining failure-cascades; and identifying the various attributes of recovery. This would draw on network theory, game theory and simulation, including agent-based simulation; an examination of the use of big data to enhance network resilience; and security and privacy issues. Given the widespread agreement that information sharing within and across all sectors is a key contributor to resilience, there is a need to better understand and manage the associated privacy and security concerns in information sharing.

Define resilience engineering and how can it contribute to overall societal resilience. This should include determining and disseminating the common factors of resilience engineering and developing and examining cross-case comparisons from disruptive events that impact on multiple sectors to identify the common factors affecting resilience. Such an effort would also benefit from a systematic literature review and the development of a capability to extend to future scenarios, both for estimating the positive effects of resilience engineering and enabling public communication to include education, dissemination and engagement.

Move beyond a static focus on 'externalised' and 'internalised' aspects of city design to be prepared to better address challenges such as climate change and other expected and unexpected shocks to the urban systems. Develop an understanding of the way in which 'grey', 'green', and 'blue' infrastructure work; how their components deliver reliability; and how their interconnectedness and interdependencies deliver feedbacks. Examine co-design of projects and 'hybrid-engineered' systems that consist of both manufactured and living components. Such systems should have an element of self-healing to them. Develop new, holistic design tools for planning and for retro-fitting. This should lead to secure, adaptive resilience and provide for 'evolutionary resilience' against those events or disruptions that we presently do not know or anticipate.

It follows from the above that education systems need to evolve to be more open-ended and challenge-driven. Thus, for example, while it is useful that some higher education programmes in river and coastal engineering are already multidisciplinary and embedded in communities of practice, they should go further, creating lifelong relationships with their students to help them continually evolve their analytical toolkits in the face of uncertain futures. Along the way, we would develop an international cadre of 'trans-disciplinarians' as well as a new common language to be used in our discussion of resilience.

Learning from ecology and ecosystems
Using lessons from studying how ecological systems respond to perturbation and new circumstances, securing 'adaptive' resilience but ensuring capacity for evolutionary resilience through new structures, components, networks and interactions. This will require the need to recognise that some things may be lost but this provides space for new components, interactions and growth. Examples include:

- using understanding of ecology and biology as analogues for building resilience in other systems, for example, ant burrowing behaviour informing approaches to effective search and recovery strategies after earthquakes
- direct integrated management of natural and built resources to effect enhanced resilience, for example, floodplain restoration to prevent inundation of urban areas
- adopting evolutionary responses to change in conditions such as crossing environmental thresholds to new system states in order to secure persistence of function and broad characteristics, for example, 'novel ecosystems'[27].

[27] Hobbs, RJ; Higgs, ES; and Harris, JA. 2014. Novel ecosystems: concept or inconvenient reality? Trends in Ecology and Evolution 29, 645 – 646.

Understanding global systems

Develop the capability to examine complex global issues including trade, transportation and communications from a networked systems perspective; other examples include supply chains and the 'Internet of Things'. Features might include network mapping, data acquisition, the identification of failure points and resultant cascades, understanding the capacity for coping under stress and recovering, as well as future trends that include the impact of climate, the global economy, population migration, and geopolitical influences.

A comprehensive, international examination of the resilience of marine infrastructure, including its support to global trade, as well as food and energy resources.

Develop a better understanding of the resilience of the future transport system for moving people and goods, in the context of increased reliance on these systems in developing countries, anticipated population growth and urban migration leading to increased congestion, and the introduction of new technologies. Future systems will be complex, dependent on big data, and are likely to include autonomous vehicles. Climate change will have a major impact on these systems, including the eventual change from an oil dependent transport system and changes in individual behaviours.

Develop an understanding of the increased disaster risk associated with urbanisation and development coupled with the effects of climate change. Many urban areas already have substantial vulnerabilities, including sub-standard infrastructure and building environments, and socio-technical inequalities.

Examine whether we can use digital technology to more effectively manage the limits of legacy physical infrastructure such as tunnels and sewerage systems. There is simply not enough money to address the shortcomings and vulnerabilities of this infrastructure. Deficiencies are becoming increasingly apparent even during non-crisis times, compounding the safety, well-being and growth of the communities in which they are located. An example would be to use flood prediction models and sewer line sensors to alert the community about flood conditions and, over the medium to long term, assist in the identification of possible solutions.

Incentives

Improve the capacity for capital markets to understand, measure and reward actions that enhance resilience. A specific focus could be on the impacts related to climate change. Work with academia and corporations to create standards and metrics to assess risk and resilience in this sector. Work with the investment community to make resilience a condition of gaining access to capital at more attractive lending rates. This implies inclusion of resilience metrics in credit scoring systems. Examples of incentives could include lower insurance premiums and cheaper sources of capital for more resilient organisations.

Develop an understanding of the processes and incentives needed to engender public involvement in actions to achieve resilience. Community-based planning and design has been used in other fields. We need to understand best practices, such as participatory processes, and the challenges to implementation in order to overcome them. Other features might include educational platforms or ‘studios’; the use of media, including social media; and robust stakeholder engagement models that recognise that while we may be specialist providers of knowledge, we are all generalist consumers of the resulting socio-technical systems.

Examine incentives to retro-fit existing systems to be more resilient, including developing strategies and technical standards.

Success and failure are often measured in terms of monetary gains or monetary savings. Resilience requires an additional set of metrics, for example, lives saved, degrees of warming or elevation of sea level avoided. Other convergent or parallel indicators, such as those developed for water security, human development and sustainability goals, may be a starting point in a broader consideration of resilience indicators.

Findings and recommendations for the Lloyd's Register Foundation

Resilience engineering is an emerging discipline and the previous chapter gives examples of activities that could support improved resilience in socio-technical systems. However the Foundation acting alone cannot make progress addressing all these complex multi-domain and multidisciplinary issues. It is important for the Foundation to act in areas where it can best make a distinctive impact in delivering its charitable mission.

There is widespread interest internationally in developing resilience as a response to known and unknown threats and appendix 2 illustrates some of the other organisations who are already investing in improving resilience. Given the scope and complexity of the issues associated with resilience, it is essential that any Foundation activities in this space be directed towards actions that maximise impact and societal benefit while leveraging the activities being pursued elsewhere.

Many of the critical infrastructure sectors supported by the Foundation do not presently possess metrics and standards for the enhancement of resilience. Progress has been inhibited by complexities and interdependencies within and among these sectors.

The Foundation could play a unique role in supporting efforts to convene and support research across national jurisdictions that involve both public and private sector practitioners. These efforts could be directed at building the resilience within and between critical infrastructures at a global scale, for example through developing new knowledge, indicators and metrics of resilience leading to standards, codes and best practices.

Findings and recommendations

Resilience engineering is one of the research priorities identified in the Foundation's strategy. It is an emerging research discipline which the Foundation can help to develop. At its heart is the concept of building systems, structures, infrastructures, organisations and associated human and social capacity which can respond appropriately (not catastrophically) to foreseen and unforeseen stresses. Such stresses might include physical (weather, flooding, explosions, impacts), economic (economic downturn, regulation, business model failure), social (management, poor training, criminal intent, labour actions) and technological (new materials, sensors, emergent properties of technological systems) factors. Although this is an emerging field there is much interest in the concept of resiliency and it is being propagated through organisations such as the US Department of Homeland Security, UK Cabinet Office, UN agencies and Rockefeller Foundation, as a more appropriate and robust response to complex risk and safety issues.

The Foundation is uniquely positioned to play a leading role in an international effort to better understand, communicate and improve resilience towards safety of life and property and in the Foundation's strategic sectors. On the next pages are recommendations on where the Foundation could invest in resilience engineering, with the aims of maximising benefit to society while also leveraging, and not duplicating, activities underway elsewhere.

Recommendation one: The Foundation should lead work to improve resilience within critical infrastructure sectors

The Foundation can bring a substantial societal benefit by building the resilience of critical infrastructure sectors. This is the primary recommendation of this review. Society depends on the proper functioning of essential services such as food and water, energy, transportation, telecommunications, the built environment and healthcare. These sectors are increasingly complex and interdependent, acting at a global scale, and making them susceptible to catastrophic and cascading failure under stress.

The Foundation can build resilience, for example, through a programme addressing:

- governance: incentives, standards and rules
- capacity building and engagement: professional development, publications, communication and public engagement
- data and supporting tools: shared datasets, modelling and simulation, decision support
- international and global scale networks: studies of global systems, supply chains, knowledge networks.

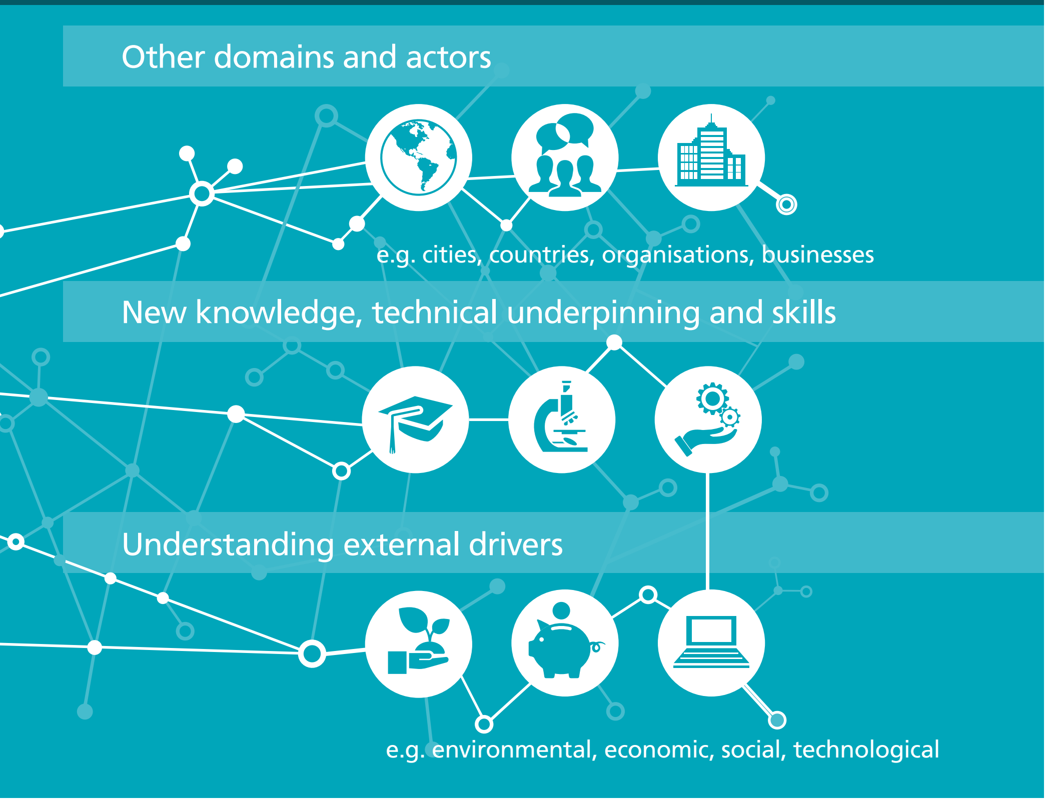
Leading role for Foundation

To build resilience within and between critical global sectors

e.g. marine, energy, food and water, telecommunications, healthcare, transport

Figure 2: Recommendations for leading and supporting roles in resilience engineering

Supporting role for Foundation



Recommendation two: The Foundation should support work to improve resilience in other application domains (for example, organisations, cities, countries)

There is growing and substantial interest in wider society in building resilience. For example, the Rockefeller Foundation holds resilience as one of its primary objectives. It funds a substantial programme called 100 Resilient Cities that supports 'chief resilience officers' to be employed in cities across the globe. The UN is promoting resilience through the Sendai Framework which was adopted in 2015. Its aim is "the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries". It has a target to "substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030". Other players such as the US Department of Homeland Security, National Institute of Standards and Technology, the UK Cabinet Office and the British Standards Institute are supporting activities and guidance to build resilience in organisations and businesses, in communities and in the built environment.

In implementing recommendation one above, the Foundation could work with others to ensure that knowledge, skills, tools and networks developed within infrastructure sectors are shared between application domains (cities, countries etc), and all those with a wider vision for a safe, secure and resilient society.

Recommendation three: The Foundation should support the technical underpinnings and skills base needed to build resilience in critical industrial sectors and to mature the discipline of resilience engineering

It is important for the Foundation to act in areas where it can best make a distinctive impact in delivering its charitable mission

Resilience depends on the ability to monitor, prepare, anticipate, adapt, respond and learn. These activities individually all require strong technical foundations and skills, and collectively the systems theory to understand resilience in complex socio-technical systems is needed. In addition the resilience of our critical infrastructures is dynamic. There are many external factors that can enhance or degrade the resilience of the critical systems on which society depends. These include environmental, economic, social and technological threats and opportunities. Many other funders are working to build technical foundations and skills and to understand and to ameliorate these external factors. But there is still a role to play for the Foundation, not only in providing leadership with other funders to invest in a cohesive way, but also identifying where Foundation funding can bring added value in partnership with others, addressing the Foundation's charitable mission. This added value often arises in the Foundation's ability to work across international boundaries, to fund translational research ensuring useful tools and techniques arise from fundamental research results and from its relationship with LR to accelerate the application of research.

In implementing recommendation one, the Foundation should work with the wider scientific community to secure the fundamental understanding and skills needed for resilient critical infrastructures.

Appendix 1: Participants and contributors

Participants in the Lloyds Register Foundation workshop at Stevens Institute of Technology, 15-17 April 2015 and contributors responding through the open consultation process.

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Vincent Doumeizel
Tara Forde
Christopher Frost
Taku Fujiyama
Kazuo Furuta
Shiv Ganesh
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Simon Jude
Ben Knight
Dana Kochnower
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Jalal Mapar
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Claus Myllerup
Jaroslav Mysiak
Richard Neilson
Blythe Nobleman
Piotr Omenzetter
Douglas Owen
Payal Patel
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Patrick Wolfe
Guo Xiong Wu
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Appendix 2: Other major programmes and initiatives in resilience and resilience engineering

This appendix has been compiled through responses to the open consultation on the draft of this document. It identifies activities underway or planned by other organisations.

100 Resilient Cities programme – Rockefeller Foundation According to their website 100RC is dedicated to helping cities around the world become more resilient to the physical, social and economic challenges that are a growing part of the 21st century. 100RC supports the adoption and incorporation of a view of resilience that includes not just the shocks – earthquakes, fires, floods, etc – but also the stresses that weaken the fabric of a city on a day-to-day or cyclical basis. Examples of these stresses include high unemployment; an overtaxed or inefficient public transportation system; endemic violence; or chronic food and water shortages. By addressing both the shocks and the stresses, a city becomes more able to respond to adverse events and is overall better able to deliver basic functions in both good times and bad, to all populations.

Cities in the 100RC network are provided with the resources necessary to develop a roadmap to resilience along four main pathways:

- financial and logistical guidance for establishing an innovative new position in city government, a chief resilience officer, who will lead the city's resilience efforts
- expert support for development of a robust resilience strategy
- access to solutions, service providers and partners from the private, public and NGO sectors who can help them develop and implement their resilience strategies
- membership of a global network of member cities who can learn from and help each other.

Through these actions, 100RC aims not only to help individual cities become more resilient, but will facilitate the building of a global practice of resilience among governments, NGOs, the private sector and individual citizens.

www.100resilientcities.org

US National Institute of Standards and Technology Announced in February 2015 the creation of the Community Resilience Center of Excellence. The centre is "working with NIST researchers and partners from 10 other universities, the center will develop computer tools to help local governments decide how each can best invest resources intended to lessen the impact of extreme weather and other hazards on buildings and infrastructure and to recover rapidly in their aftermath".

www.nist.gov/el/building_materials/resilience/research-center-help-communities-increase-resilience-to-disaster.cfm

US Department of Homeland Security Presently in the final stages of creating the Critical Infrastructure Resilience Center of Excellence.

Resilience Engineering Association According to the website the REA has the following aims and programmes:
Purpose: To develop a community of practitioners and users of resilience engineering
Means: To create ways to share experience and learning, such as:

- summer schools and industry partnerships
- conferences and workshops
- books and papers.

To create a sense of identity:

- a collegial community of practitioners and users
- a confederation of industrial partnerships
- opportunities to speak with a common voice in professional and industrial settings.

To promote a shared understanding of what resilience engineering means:

- debate and discussion
- examples of applications in diverse ways and fields
- point and counterpoint.

www.resilience-engineering-association.org

The UK Engineering and Physical Sciences Research Council (EPSRC) has supported several activities that address issues related to resilience engineering:
www.epsrc.ac.uk/skills/fellows/areas/priorityareas/engineering/priorityareas/globalgrandchallenges/
www.epsrc.ac.uk/funding/calls/energyresilientmanufacturing/
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/I035773/1
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/H021779/1

The VTT Technical Research Centre of Finland Ltd has supported technology and innovation research in several areas relevant to resilience engineering, including:

- nuclear power related
- safety in complex systems
- human factors in systems engineering.

www.vttresearch.com

The IEEE Industrial Engineering Society "...aims to serve as an interdisciplinary forum and source of reference for the development, implementation, assessment and dissemination of novel and effective methods to enhance, modernise and improve resilient technologies".

http://vps.ieee-ies.org/resia-home

New Zealand's Resilient Organisations collaboration builds effective capability building through research activities with significant impacts on policy and practice.

www.resorgs.org.nz

UNISDR (United Nations Office for Disaster Risk Reduction) Making Cities Resilient Campaign and the New Ten Essentials for Making Cities Resilient. A set of essentials and indicators are developed by a team of experts and organisations. The primary objective of these essentials is to be operational, adaptive and applicable to all, encouraging cities towards their implementation.

The proposed New Ten Essentials build upon the previous essentials, and they are interlinked to the UN Sendai Framework for Disaster Risk Reduction with priorities for action, representing a transition to a stage of implementation.

It is expected that the Sendai Framework for DRR and the New Ten Essentials will pave the way for implementing new policies on urban resilience and support governments in implementing strategies that include targets and are time bound. The New Ten Essentials for Making Cities Resilient are:

1. organise for disaster resilience
2. identify, understand and use current and future risk scenarios
3. strengthen financial capacity for resilience
4. pursue resilient urban development and design
5. safeguard natural buffers to enhance the protective functions offered by natural ecosystems
6. strengthen institutional capacity for resilience
7. understand and strengthen societal capacity for resilience
8. increase infrastructure resilience
9. ensure effective disaster response
10. expedite recovery and build back better.

A team of experts from multiple organisations are currently working on developing applicable indicators under each essential that will be used by local governments as action points to measure resilience. The developed indicators are to be assessed by local government officials and piloted in a number of cities and the final set is to be released for use by all local governments and city officials by March 2016.

www.unisdr.org/campaign/resilientcities

University of Tokyo According to its website, the Resilience Engineering Research Center (RERC) was established in April 2013 to promote research into the principles and methodologies for realising resilient systems. The centre intends to contribute to a safe and secure society by establishing a new risk management framework that exceeds the conventional and static approaches of risk management.

http://rerc.t.u-tokyo.ac.jp/index_en.html

Adaptation and Resilience in the Context of Change (ARCC) Network The performance of the UK built environment and infrastructure systems is critical to national well-being, the growth agenda and economic competitiveness. However, these complex and interdependent sectors face serious challenges if they are to remain resilient to expected future changes.

EPSRC-funded projects provide the focus of the ARCC network, looking at adaptation and resilience in buildings, urban environments, transport networks, water resources and energy systems. Through co-ordinated activities involving researchers and stakeholders, the network maximises and accelerates the benefits of research to support sustainable urban environments and national infrastructure systems.

By providing a comprehensive focal point for knowledge exchange, information and engagement opportunities for adaptation, the ARCC network seeks to meet policy and practice requirements for credible and salient evidence from across the research community.

www.arcc-network.org.uk/about-arcc/

Appendix 3: Further reading

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Besharati, RZ; Eshraghniaye, JA (2014) A framework for resiliency assessment of power communication networks. Scientia Iranica. Transaction E, Industrial Engineering 21: 2399-2418.

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De Florio, V; Sun, H; Blondia, C (2014) Community resilience engineering: reflections and preliminary contributions. Software Engineering for Resilient Systems 8785: 1-8.

DesRoches, S and Murrell, S (2014) Transportation infrastructure resiliency guidelines for the Port Authority of New York & New Jersey. T&DI Congress 2014: pp. 649-658.

Fitzmaurice, M (2014) Improving resiliency in communications systems in public transit after severe weather events. ASME Proceedings. Joint Rail Conference, Colorado Springs, Colorado, 2-4 April.

Flynn, SE (2015) Bolstering critical infrastructure resilience after superstorm Sandy: Lessons for New York and the nation, www.northeastern.edu/resilience/wp-content/uploads/2015/04/Bolstering-Critical-Infrastructure-Resilience-After-Superstorm-Sandy.pdf

Heffner, K (2015) Cyber resiliency: an industry perspective. AAAS Annual Meeting, 12-16 February.

Hollnagel, E (2015): FRAM - the functional resonance analysis method: modelling complex socio-technical systems.

Jabareen, Y (2013) Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. Cities 31: 220–229.

Jackson, S; Ferris, TLJ (2013) Resilience principles for engineered systems. Systems Engineering 16: 152–164.

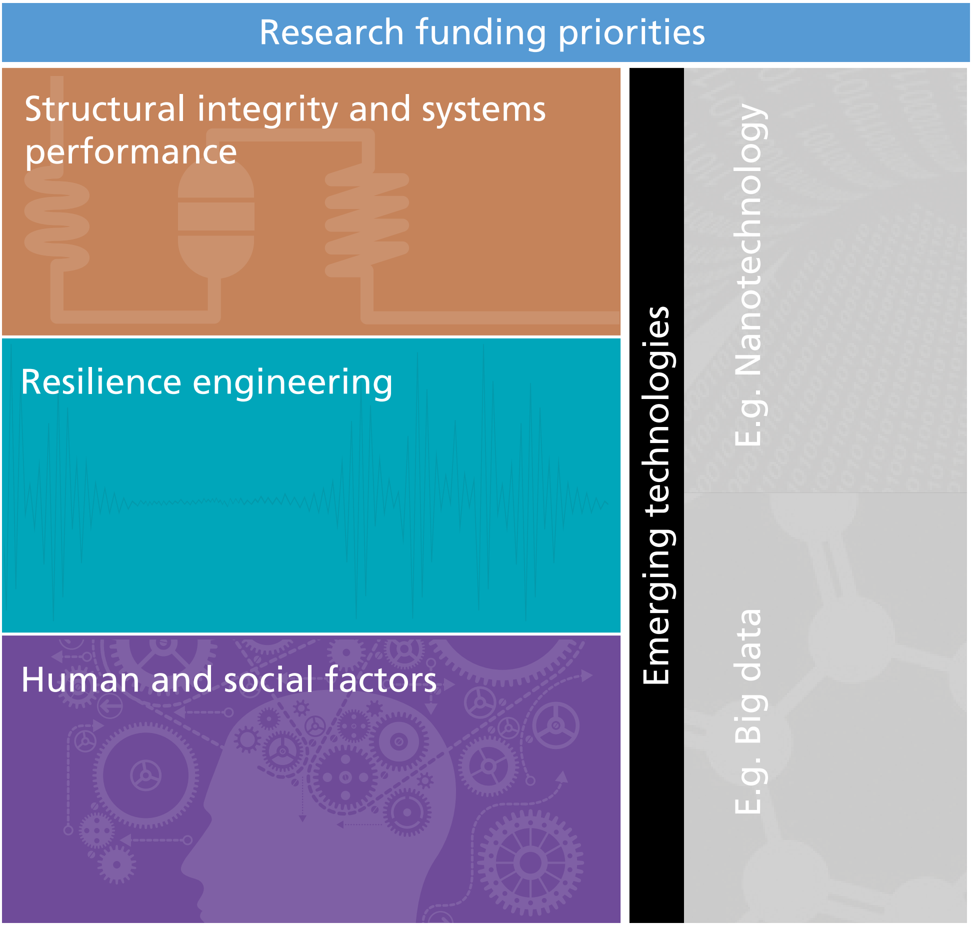
The Joint Research Centre (2015), The challenge of resilience in a globalised world. EUR27180 EN, ISBN 978-92-79-48439-1

Mackey, W (2013) Have North America and the Caribbean shown resiliency to recent natural disasters and human-induced accidents? A debate on the issues (an application of systems engineering and systems thinking) INCOSE International Symposium, Philadelphia, PA, 24-27 June, Volume 23: 1587–1609.

Madni, AM; Jackson, S (2009) Towards a conceptual framework for resilience engineering. Systems Journal, IEEE 3: 181-191.

Shirali, GhA; Mohammadfam, I; Ebrahimipour, V (2013) A new method for quantitative assessment of resilience engineering by PCA and NT approach: A case study in a process industry. Reliability Engineering & System Safety 119: 88–94.

Appendix 4: Research funding priorities



The Foundation's research priorities should not be viewed in isolation; they are interlinked and can be understood at different scales. These range from nanoscale materials to individual components within complex systems to the interconnected networks of infrastructure on which society depends, and from the actions and behaviours of individuals of organisations and wider society.

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