A Foresight Review of Resilience Engineering: Designing for the Expected and Unexpected


This document is a draft report on the emerging field of Resilience Engineering. The authors welcome comments, amendments and new inputs which should be sent to resilienceworkshop@stevens.edu by August 14, 2015.

Editor: Michael S. Bruno, Stevens Institute of Technology
About 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 (the 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

To be included in final version

Foreword

To be included in final version
Background

1. This report commissioned by Lloyd’s Register Foundation explores the emerging field of Resilience Engineering. How could 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, organizations and communities around the world?

2. Lloyd’s Register Foundation has identified Resilience Engineering as one of its strategic funding priorities¹, for the Foundation’s research grant giving. 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, capitaly intensive assets in the energy, maritime and transportation 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.

3. 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.

4. A workshop was held on April 15-17, 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 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.

5. 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?

6. This report builds on the workshop findings and recommendations and, following a period of consultation, it will provide recommendations to the Foundation on how to support this emerging field of knowledge. Contributors to the April, 2015 workshop are listed in Appendix 1.
What is Resilience Engineering?

- Resilience is a term common to many fields of study
- 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

8. 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 and/or adapt to a vast range of disruptive events. These systems include, among others, ecological systems (Holling’s often-cited 1973 paper),\(^2\) physical (e.g., structures designed against earthquake loading), complex systems (e.g., the supply chain made resilient using methods of redundancy), and human communities (e.g., 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. This has prompted a debate about the most appropriate definition of the term “resilience”. Norris et. al. (2008)\(^3\) provide a useful summary of the applications of the term over the last 40 years. They conclude that in the context of human communities, organizations and societies, 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.”

9. The definition of resilience adopted by the Rockefeller Foundation’s 100 Resilient Cities initiative is “resilience 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. It is also noteworthy that the Rockefeller

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Foundation’s definition includes specific mention of two basic types of disruptions: short-term, acute shocks and longer-term, chronic stresses.

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

- British Standards Institution: Guidance on organizational resilience4: “Organizational resilience is the ability of an organization 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”
- U.S. President Policy Directive 21 - Critical Infrastructure Security and Resilience (February 12, 2013): “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.” 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.

11. Turning our attention to the emerging field of Resilience Engineering, we note again that the discipline is still in its earliest stages. The employment of 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 rigor is needed to support its study, particularly when describing the stochastic

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7 http://www.iso.org/iso/37120_briefing_note.pdf
nature of resilience along a time domain. When it comes to engineered systems and living systems, a core attribute is that they are inherently interconnected. However, too often their interdependencies and shared vulnerabilities are not well understood. As stated by Woods (2015)\(^8\), *“the future is intensely technological and intensely human.”* Accordingly, the study of resilience and Resilience Engineering must be trans-disciplinary and must draw from expertise across multiple sectors and jurisdictions.

12. Certainly, it is useful to contemplate the composition of abilities or methodologies that are required in order to make a meaningful contribution towards increasing resilience. Borrowing from lessons learned in a number of areas (Hollnagel et. al. (2006)\(^9\)) the following are suggested:

a. The ability to **monitor**. Knowing what to look for, or being able to monitor that which is or could seriously affect the system’s performance – positively or negatively. The monitoring must cover the system’s own performance as well as what happens in the environment. Monitoring supports preparedness.

b. 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, thus preventing significant mal-effects.

c. 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 the right experience.

d. 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.

13. Turning our attention to engineered systems, Hollnagel\(^10\) suggests “A system is resilient if it can adjust its functioning prior to, during, or following

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\(^10\) [http://erikhollnagel.com/ideas/resilience-engineering.html](http://erikhollnagel.com/ideas/resilience-engineering.html)
events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions”. Linkov et. al. (2014)\textsuperscript{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 critical functionality, not the pre-existing system. 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 would likely have been established in a much earlier era) with new socio-technical systems able to deliver critical functionalities differently (e.g smaller spatial footprint, cheaper, less carbon-generative, etc.). Mutchek and Williams (2014)\textsuperscript{12} suggest that this sort of resilience should lie at the heart of emerging “smart grids” or “smart cities”. Achieving this ‘resiliency by design’, wherein the system function, and not the system itself, is preserved, lies at the heart of Resilience Engineering.

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Consultation Point:

- We welcome references and examples of standards, guidance and policies which support the integration of resilience as a primary design endpoint.
- We welcome examples – if they exist – of the application of Resilience Engineering to the design or improvement of actual engineered systems.

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Understanding Resilience through Case Studies

15. 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.

Example 1: The Law of Unexpected Consequences: Hurricane Sandy in New York City.

16. 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 meters in some areas) along the coast of New Jersey and inside New York Harbor. Throughout the U.S., 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. (Aon Benfield (2013)\textsuperscript{13}).

17. 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 3 days after landfall, and was nearly fully operating in less than a week. The delivery of containerized cargo through the Port of New York and New Jersey, representing 61.2\% percent of all such cargo in the North Atlantic in 2012 (PANYNJ (2013)\textsuperscript{14}), 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 (e.g. Halifax) that had excess capacity.

\textsuperscript{14} \url{http://www.panynj.gov/port/pdf/2012_trade_statistics_sheet.pdf}
18. 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 of 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.

Example 2: The 2011 Tohoku earthquake, tsunami and nuclear disaster
19. This text still to be developed.

Example 3: The 2003 North American and European cascading power blackouts
20. In 2003, both North America and Europe 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.

21. 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 4 days. An overload on the grid that distributes electricity to the eastern United States 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.
22. 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 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 the potential for even more severe consequences.

Example 4: Flooding events in England and Wales

23. Over the last decade, England and Wales have experienced frequent water related challenges. The floods of Boscastle (2004), Gloucestershire (2007), Cumbria (2009) and Somerset (2014) constitute a challenge to the resilience of several critical functionalities. Each of these events was local, and yet each resulted in considerable disruption and loss of life and property. At Boscastle and in Cumbria, hundreds of properties were destroyed and although the government response was quick, it emphasised traditional engineering solutions – in effect “hardening” the “targets” of likely future events. In Gloucestershire and Somerset, the impacts were both local (extensive property damage and 3 deaths) and more widespread, with national food and transport systems more severely impacted.

24. After the Gloucestershire floods in July, 2007 the government of the day commissioned a national review of flood preparedness: the “Learning Lessons from the 2007 Floods” (or the “Pitt Review”). 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. However in 2014, under a new government, flooding in Somerset became a focus of political disagreement.
response included a 20-year plan including dredging, more permanent pumping sites, and a tidal barrier, estimated to cost £100m\textsuperscript{15}. This political and literal retrenchment, to policies to build structures that will hold back future waters, highlights the complex socio-technical nature of such events and systems, and the need for trans-disciplinary resilience approaches that include social and political considerations.

\textsuperscript{15}Taken from: \url{http://www.bbc.co.uk/news/uk-england-somerset-26157538}
Impacts, Trends, and Opportunities: The Challenges to Resiliency

- Present and future challenges include ‘external’ threats from a range of hazards, and ‘internal’ threats from organizational deficiencies
- Potential solution pathways are necessarily trans-disciplinary, and include engineering, the natural, physical, and social sciences, economics, and policy

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

- **Uncertainty**, which drives a need for more accurate and robust predictive ability, as well as the need for adaptability, but accepting that some level of uncertainty will always exist
- **Globalization**, which drives a need to better understand the risks to global businesses that depend on infrastructure and networks that operate across multiple jurisdictions
- **Lack of parameters by which to characterize resilience**, which 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**, which drives a need for participatory approaches that can identify and nurture a “commonality of purpose”, and lower or eliminate the barriers to 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 programs** at all levels, from practitioners and researchers to business leaders and policy makers. Since by definition the field of 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. 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 organizations and domains via vehicles that can protect privacy and proprietary information.

- **Excessive focus by managers around current status** and on single performance indicators, e.g. ‘the bottom line’. Prescriptive adherence to safety methods focused on the avoidance of accidents (Safety I) rather than the safety and resilience of the whole system (Safety II) can be a barrier to positive change. This will require an acceptance of adaptive and evolutionary configurations of the system and the need to plan over longer time cycles.

- **Rapid fluctuations in demand** fueled by information availability, 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 (an increasing aged population) and migration from conflict and poverty, requiring housing, health, and other critical service interventions, challenging the resilience of these systems.

27. Table 1 provides examples of challenges (and associated timelines) to resilience in each critical lifeline sector identified during the April 2015 workshop, along with potential resiliency 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 resiliency solutions to short, medium and long-term challenges.
Table 1: A Future Timeline of Challenges to Resiliency and Potential Solution Paths

<table>
<thead>
<tr>
<th>Sector</th>
<th>Short Term (0-5 years)</th>
<th>Medium Term (5-10 years)</th>
<th>Long Term (10-20 years)</th>
<th>Potential Resiliency Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthcare and Medicine</td>
<td>● Highly fragmented health care system</td>
<td>● Surge capacity degraded by cost-saving efforts to promote system-wide efficiency improvements</td>
<td>● Drug-resistant pathogens ● Pandemic</td>
<td>● Effective and secure information sharing</td>
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<tr>
<td></td>
<td>● Aging population</td>
<td>● Aging population</td>
<td></td>
<td>● Invest in global surge capacity, enabled by design, and analytical tools</td>
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<td></td>
<td>● Data and information collection and sharing</td>
<td>● Pandemic</td>
<td></td>
<td>● Address health care capacity inequities in developing vs developed nations</td>
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<tr>
<td></td>
<td>● Population growth, mobility and migration</td>
<td>● Climate Change</td>
<td></td>
<td>● Develop better understanding of potential unintended consequences of health care solutions, in particular during crises</td>
</tr>
<tr>
<td></td>
<td>● Conflict</td>
<td>● Inequities in health care system capacity across nations</td>
<td></td>
<td>● Develop incentives for resilient design and practices</td>
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<tr>
<td></td>
<td>● Natural disasters</td>
<td>● Personalized medicine.</td>
<td></td>
<td>● Enable self-reliance and well-being, e.g., using social media</td>
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<td></td>
<td>● Terrorism</td>
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<td></td>
<td>● Education, training, public communications</td>
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<tr>
<td></td>
<td>● Virulent and contagious disease outbreak</td>
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<tr>
<td>IT and Communications</td>
<td>● Security and privacy issues</td>
<td>● Security and privacy issues</td>
<td>● Artificial intelligence and self-learning systems</td>
<td>● Effective and secure information sharing</td>
</tr>
<tr>
<td></td>
<td>● Monopolies</td>
<td>● Localized systems (off the grid)</td>
<td></td>
<td>● Design for resilience, including retro-fit</td>
</tr>
<tr>
<td></td>
<td>● Disruption to satellite comms.</td>
<td>● Scarcity of essential materials</td>
<td></td>
<td>● Back-up power or off-grid</td>
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<td></td>
<td>● Power outages</td>
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<td>● Localized communications capability, including prioritization schemes</td>
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<td></td>
<td>● Disruption of the materials supply chain</td>
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<td>● Resiliency standards and codes for emerging technologies</td>
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<td></td>
<td>● Conflict</td>
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<td></td>
<td>● Education, training, public communications</td>
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<td>● Natural disasters</td>
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<td></td>
<td>● Terrorism</td>
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<td></td>
<td>● Increased</td>
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18
<table>
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<tr>
<th>Power and Utilities</th>
<th>Communications</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Aging infrastructure</td>
<td>• Critical lifeline systems designed for temporary operation without access to power</td>
</tr>
<tr>
<td>• Heat islands</td>
<td>• Education, training, public communications in terms of short (civil contingency) and longer term resilience</td>
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<tr>
<td>• Population growth and migration</td>
<td>• Build a capability to anticipate, assess and adapt to changes (environmental, socio-technical, and geo-political)</td>
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<tr>
<td>• Cyber attacks</td>
<td>• Portable systems to adapt to population migration</td>
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<tr>
<td>• Conflict</td>
<td>• Incentives for resilient design and retrofitting</td>
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<tr>
<td>• Natural disasters</td>
<td>• Real-time monitoring</td>
</tr>
<tr>
<td>• Terrorism</td>
<td>• Add resiliency to utility performance metrics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transportation and Shipping</th>
<th>Education, training, public communications in terms of short (civil contingency) and longer term resilience</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Aging infrastructure</td>
<td>• Regulations and policies that can keep up with technology changes</td>
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<tr>
<td>• Autonomous systems</td>
<td>• Big Data solutions,</td>
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<tr>
<td>• Larger vessels</td>
<td>• Unforeseen changes in flows of goods and people</td>
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<tr>
<td>• Aging infrastructure</td>
<td>• De-carbonization</td>
</tr>
<tr>
<td>• Climate change</td>
<td>• Distributed systems</td>
</tr>
<tr>
<td>• Heat islands</td>
<td>• Disruptive technology development</td>
</tr>
<tr>
<td>• Population growth and migration</td>
<td>• Critical lifeline systems designed for temporary operation without access to power</td>
</tr>
<tr>
<td>• Emerging, disruptive technologies (e.g. “internet of things”)</td>
<td>• Build a capability to anticipate, assess and adapt to changes (environmental, socio-technical, and geo-political)</td>
</tr>
<tr>
<td>• Impact on large populations of a movement away from centralized systems and towards distributed systems and renewables</td>
<td>• Portable systems to adapt to population migration</td>
</tr>
<tr>
<td>• Climate change</td>
<td>• Incentives for resilient design and retrofitting</td>
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<tr>
<td>• Heat islands</td>
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<td>• Add resiliency to utility performance metrics</td>
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<tr>
<td>• Emerging, disruptive technologies (e.g. “internet of things”)</td>
<td>• Cyber-physical security improvements</td>
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<td>• Unforeseen changes in flows of goods and people</td>
<td>• De-carbonization</td>
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<td>Food and Water</td>
<td>Built Environment</td>
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</table>
| that can operate only in mega ports  
- Conflict  
- Natural disasters  
- Terrorism  
- Changes in underpinning power sources e.g. automobile  
- Electrification  
- disruptive technologies  
- Population growth and migration, and the associated changes in flows of people and cargo  
- using sensors, modeling 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  |  
| Climate change (droughts, floods)  
- Environmental disaster, e.g., chemical spill  
- Sanitation  
- Population growth and migration  
- Disease  
- Conflict  
- Natural disasters  
- Terrorism  
- Changing diets in the emerging economies  
- Climate change (droughts, floods)  
- Environmental degradation  
- Sanitation  
- Population growth and migration  
- Civil unrest  
- Climate change (droughts, floods)  
- Environmental degradation  
- Sanitation  
- Population growth and migration  
- Conflict  
- Disease  
- Incentivize the distribution systems to address inequalities  
- Improve communications and notification mechanisms in inter-linked systems  
- Education, training, public communications  
- Low-energy desalinization  
- Enhanced food preservation  
- Reduction of wasteful water use  
- Behaviour change  
- Local production and distribution e.g. ‘urban farms’  |  
| Aging and non-resilient infrastructure  
- Population growth and  |  
| Climate change (droughts, floods, heat shocks)  
- Aging population  
- Performance-based building codes, planning for resilience  
- Incentives for resilient designs and retro- |
<table>
<thead>
<tr>
<th>Migration (URBANIZATION)</th>
<th>Rapid growth of “green” and “blue” infrastructure</th>
<th>Fitting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conflict</td>
<td></td>
<td>Proper balance among grey, blue, and green infrastructure</td>
</tr>
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<td>Natural disasters</td>
<td></td>
<td>Education, training, public communications</td>
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<td>Terrorism</td>
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<td>Public Participation</td>
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<td>Socio-technical vulnerability</td>
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<td>Inadequate capacity of local governments</td>
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</table>

Consultation Point:

- We welcome an assessment of these or other future trends and challenges, and the associated solution paths.
Impacts, Trends, and Opportunities: Toward Engineered Solutions

- 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 resiliency goal of preserving critical system functionality in the face of anticipated and unanticipated conditions
- Retrofitting existing systems is a serious challenge

28. To this point this report has been broad-based, addressing the challenges and activities associated with improving the resilience of communities, infrastructure, and complex networks. Given the mission of Lloyd’s Register Foundation “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 improving our ability to understand, communicate, and improve the resilience of engineered systems. Engineered systems are often in reality components of complex, interconnected, interdependent, and often 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.

29. Taken on their own, each element of an engineered system, in any sector, can be assessed for resiliency by simply examining – e.g., via physical or computational simulations – failures caused by events that exceed the design conditions. 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 modeling and assessment capability, would require the sort of advances as those achieved in system risk assessment in the 1960's and early 1970's. 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. With such a capability in place, the exploration of potential design modifications, upgrades and retrofitted solutions required to formulate a more resilient system could be objectively achieved.

30. 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 data to support modeling. Due to 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 this aspect of the framework development to be achieved through 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 however place a demand on advances achieved through Big Data initiatives.

31. The discussion of risk should emphasize the opportunities for investment, and our work should ultimately be less about minimizing 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 (Hollnagel, 2015\textsuperscript{16}). In this sense, disruptive events are an opportunity to learn and to improve system performance (see Figure 1).

![Diagram of Function, Success, Malfunction, Failure](image)

**Figure 1**: Safety 2 (top) VS Safety 1 approach\textsuperscript{17}

32. This approach to an improved resilience of engineered systems is embodied in “Performance-Based Engineering” (PBE), 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, 2003\textsuperscript{18}). We note 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.

\textsuperscript{17} http://www.drillingcontractor.org/new-safety-perspective-focuses-on-investigating-what-goes-right-32256
33. This discussion would be incomplete without addressing the important challenge of managing ageing infrastructure. For example, Eidinger and Davis (2012) highlight in a case study on water system pipelines 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 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.

34. One final note before we leave this section of the report: as stated numerous times herein, 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. This approach ignores the experience of many actual, large-scale disruptions, in which human actions were responsible for the continuation or restoration of system functioning. A recent dramatic example was the Fukushima nuclear accident, described earlier in this report. The actions of the power plant employees demonstrated that often in such disruptive events, “people are the resource for flexibility and resilience” (Yoshizawa, 2015). 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 high-tech companies over the last decade or so.

Consultation Point:

- We welcome additional examples of engineering approaches to resiliency challenges, across the different critical lifeline infrastructures.

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35. Supporting the Uptake and Impact of Resilience Engineering

36. This section suggests 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

37. The establishment of a global, open, modeling and simulation platform, with the following attributes:

- Accepts models of physical phenomena, human behavior, 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 visualization 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, e.g., via “war-gaming” and agent-based modeling

38. Create a “Decision Exploratorium” equipped with advanced visualization (including virtual reality), the ability to generate and display “what-if” scenarios, real-time data streams, etc. Enable the discussion of problems that may not normally be discussed openly. Ultimately, this facility/capability should be expanded to a shared global environment, which could enable the examination of cultural issues that may affect decision-making.

39. Develop better communication capabilities and enable information flow between and among systems and sub-systems, down to the individual level. A resilient and safe city will be achieved through improved transparency and trust from better information (data), communications
and monitoring. Better informed individuals make better decisions (utility). Use “what-if” scenarios to find the commonalities – the nodes – between systems, and work with foresight-methods to investigate the resilience of the ‘system of systems’ to individual shocks. Aim at preparing the whole systems to withstand / recuperate from shocks and disturbances at various scales via effective knowledge sharing and faster processing of (open) data. Assign governance structure to deal with information deficit and improve communications during disturbances in the system.

**Fostering International Collaboration**

40. The establishment of a global network of researchers and practitioners, with the following attributes:

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

41. 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’ (i.e., resilient structures, systems, companies, etc.). One vehicle for encouraging strong international and inter-disciplinary collaboration could be the establishment of a “summer resiliency institute” that would gather experts from around the world and across disciplines to work intensively on a set of focused, relevant problems related to resiliency.

42. International continued professional development (CPD) intensive courses e.g. on urban resilience for local government decision-makers: to include case studies from participants and work on own ‘resilience plan’. The course might develop a set of global urban challenge scenarios over the course of 2-3 days and then develop a hands-on solution set for
participants’ own case using materials and expert input during a further 2-3 days of consultations/seminars and workshop. Lecturers would co-design the scenarios and have ‘free participatory workshop outcomes’ to use for academic purposes. Further benefits to participating academics include: forging international connections to key urban decision-makers and stakeholders for possible roll-out of other knowledge sharing and research programmes together. Benefits to local decision-makers include: access to other cities’ challenges and decision-makers’ experiences, access to broad academic knowledge and tool-kits, and co-design tailored solutions.

**Foundational Research**

43. The development of a solid theoretical foundation for the study and engineering of the resilience of socio-technical networks. This would address interconnectedness; the modeling of the two layers - social and technology, and autonomy; examining failure-cascades, and identifying the various attributes of recovery. Such an effort will need to draw on network theory, game theory, and simulation, including agent-based simulation. As this work progresses, the study should include an examination of the use of Big Data to enhance network resilience, and it should include treatment of security and privacy issues.

44. 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.

45. 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.
46. Move beyond a static focus on “externalized” and “internalized” aspects of city design so as 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. This study would need to be conducted with a trans-disciplinary view. 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. Develop the ability to examine various future scenarios in the short, medium, and long-term. Develop new, holistic design tools for planning and for retro-fitting. This effort would be designed to lead to “secure, adaptive resilience” and provide for “evolutionary resilience” against those events/disruptions that we presently do not know or anticipate. The ultimate aim is to secure human well-being.

47. It follows from the above that education systems need to evolve to be more open-ended and challenge-driven. Thus, for example, whilst it is useful that some higher education programmes in river and coastal engineering are already multidisciplinary and embedded in communities of practice, they could/should go further creating lifelong relationships with their students to help them continually evolve their analytical toolkits in the face of uncertain futures.

48. Learning from ecology and ecosystems: Using lessons from studying ecological systems responses to perturbation and new circumstances – securing “adaptive” resilience, but ensuring capacity for evolutionary resilience - new structures, components, networks and interactions. This will require the need to recognize that some things may be lost but this provides space for new components, interactions and growth, as identified above. This may be pursued in a number of modes, but in particular:

- Using understanding of ecology and biology as analogues for building resilience in other systems – e.g. ant burrowing behavior informing
approaches to effective search and recovery strategies after earthquakes

- Direct integrated management of natural and built resources to effect enhanced resilience e.g. 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 (e.g. novel ecosystems – Hobbs21 et al 2014).

**Understanding Global Systems**

49. Develop the capability to examine complex, global issues to include trade, transportation, and communications from a networked systems perspective, but could also include supply chains and systems such as the ‘Internet of Things’. Such a study would need to 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.

50. A comprehensive, international examination of the resilience of marine infrastructure, including the marine infrastructure that supports global trade, as well as food and energy resources.

51. Develop a better understanding of the resilience of the future transport system for moving people and goods, in the context of increased reliance of these systems in developing countries, anticipated population growth and urban migration and the associated increased congestion, and the introduction of new technologies. Future systems will be very complex, very dependent on Big Data, and will likely 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 behaviors.

52. Develop an understanding of the increased disaster risk associated with urbanization and development, coupled with the effects of climate change.

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change. Many urban areas already have substantial vulnerabilities, including sub-standard infrastructure and building environments, and socio-technical inequalities. It is important to address disaster risk from the standpoint of hazard exposure and vulnerability, with the aim of increasing the capacity for preparedness.

53. Examine whether we can use digital technology to more effectively manage the limits of legacy physical infrastructure. There is simply not enough money to address the shortcomings and vulnerabilities of this infrastructure (e.g., tunnels and sewer lines). These 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

54. Improve the capacity for capital markets to understand, measure, and reward actions that enhance resilience with a specific focus 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 organizations.

55. 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, and the challenges to implementation, which can hopefully lead to strategies for overcoming these challenges. A primary area of research would be the examination of "participatory processes" to engage stakeholder communities. This effort can also include the development of educational platforms, or "studios" to enable this study, including the identification and sharing of best practices, beginning with 3 to 5 cities. The use of media, including
social media, would be an important tool. To achieve the above requires a robust stakeholder engagement model, one that aspires to ascend “Arnstein’s Ladder” based on the recognition that whilst we are more or less “specialist” providers of knowledge, we are all “generalist” consumers of the resulting socio-technical systems.

56. Examine the issues associated with the need to retro-fit existing systems to be more resilient in the face of climate change and other threats, e.g., population growth and urban migration. This effort would examine the systems that are already in place, and develop strategies, technical standards, and incentives to make these systems more resilient. If done correctly, these changes would become an organic element of these systems. A primary challenge therefore is how do we incentivize actions and projects that very often will not always be visible to the users of systems?

57. In virtually all current activities, our successes and failures are measured in terms of monetary gains or monetary savings. Resilience requires a need to develop an additional set of metrics – e.g., lives saved, degrees of warming or elevation of sea level avoided, etc. There is a need here to canvas other “convergent” or “parallel” indicators (e.g. water security, human development, sustainability etc.) before launching something wholly new.

Consultation Point:

- Consultation Point: We welcome suggestions for other interventions, for example those which can be made through research and training, that will lead to more resilient structures, systems, organisations and critical infrastructures.
Resilience Engineering: implications for Lloyd’s Register Foundation

58. The discipline (trans-discipline) of Resilience Engineering is still in its infancy. However, there is widespread international and cross-sector agreement that in the face of increasing frequency and severity of known threats (e.g., droughts, floods, conflict, population migration) and the inevitable appearance of threats previously unknown, there is an urgency to make our communities, and in particular our engineered systems, more resilient to disruption. Given the mission of the Foundation “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 improving our ability to understand, communicate, and improve the resilience of engineered systems.

59. Quoting from Woods (2015) again: “the future is intensely technological and intensely human.” Accordingly, the study of resilience and Resilience Engineering must be trans-disciplinary and must draw from expertise across multiple sectors and jurisdictions. This is one area where investment from the Foundation could be transformative. Securing a ‘safe space’ where long-term, trans-disciplinary work can be pursued and piloted, and where learning from failure can be embraced as part of the transformative process, and recognizing that development of such a body of knowledge will be both evolutionary and incremental.

60. The Foundation’s strategic sectors do not presently possess metrics and standards for the enhancement of resiliency. Progress has been inhibited by complexities and interdependencies within and among these sectors. Appendix 2 lists the current and planned activities related to Resilience Engineering in other organizations and agencies. Given the scope and complexity of the issues associated with resiliency, it is essential that any Foundation investments in this space be directed towards activities that maximize impact and societal benefit while leveraging the activities being pursued elsewhere.

61. LRF 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 advancing our understanding of the benefits to global businesses and governments of...
becoming more resilient, and to initiate the process of developing understanding, indicators and metrics of resilience that can lead to the development of standards, codes, and best practices.

Findings and Recommendations

62. This report concludes that assurance of the resiliency of complex engineered systems against both known and unknown threats is essential to the charitable aims of Lloyd’s Register Foundation. The “resilience imperative” is being driven by the increasing complexity and uncertainty of our largely globalized socio-technical systems.

63. 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. Below are recommendations on where the Foundation could invest in Resilience Engineering, with the aims of maximizing benefit to society while also leveraging (and not duplicating) activities underway elsewhere.

64. Support the fundamental development of the emerging field of Resilience Engineering,
   Example areas for action:
   • Underpinning texts and publications
   • Graduate and Professional development
   • Public and end user understanding and engagement

65. Support the technical underpinning of the RE discipline for example by developing new tools and methodologies
   Example areas for action:
   • Research to develop tools, methods and technologies.
   • Support to identify and address ‘grand challenges’ for Resilience Engineering

66. Support the uptake and impact of Resilience Engineering for example by supporting development of standards, policies and measures.
   Example areas for action:
   • Development of resilience measures in critical infrastructure systems
- Support to develop guidance, policies and standards, especially those targeted where the Foundation can have the greatest impact.

67. Catalyse the resilience of critical infrastructures and complex socio-technical systems at international and global scales.
   Example areas for action:
   - Studies supporting understanding of critical international systems, for example maritime transportation, energy, food, water and other critical supply chains, the Internet of Things
   - Studies supporting anticipation, preparedness, responsiveness and adaptation of critical international systems.
   - International knowledge sharing networks

68. Support the application of Big Data methods and tools to increase our understanding and improve resilience.
   Example areas for action:
   - Broker and support discovery of sources of relevant open or closed data.
   - Support big data analytical methods towards resilience design goals
   - Support visualization of complex systems

Consultation Point:
- We welcome suggestions for other interventions in line with the Foundation’s mission and strategic aims.
- We welcome partnership with other groups or funders with complementary aims where we might develop greater impact through working in partnership
Appendix 1: a) Participants in the Lloyds Register Foundation workshop at Stevens Institute of Technology, April 15-17th 2015 b) contributors responding through the open consultation process.

To be added.
Appendix 2: Other major programmes and initiatives in Resilience and Resilience Engineering

Consultation Point: We would like to know about other organisations, including funding organisations, that are focusing work on resilience engineering. The Lloyd’s Register Foundation would also be pleased to hear from organisations interested in working in partnership to develop funded research programmes.

Related activities underway or planned include the following:

To support the 2500+ cities that are part of the “Making Cities Resilient: My City is Getting ” Campaign, a set of Essentials and indicators are developed by a team of experts and organizations. 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. Organize 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 organizations are currently working on developing applicable indicators under each essential that will be used by local governments as action points to measure resiliency. 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.

2) **100 Resilient Cities – Rockefeller Foundation**

According to the website - [http://www.100resilientcities.org](http://www.100resilientcities.org) - 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; and
- 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. We began working with our first group of 32 cities in December of 2013. In 2014, we received 330 applications from 94 countries for our second cohort, and we announced the 35 cities of round 2 in December. The last 100 Resilient Cities Challenge will open to applicants late in 2015.”
3) **U.S. National Institute of Standards and Technology**
Announced in February, 2015 the creation of the Community Resilience Center of Excellence. According to the announcement - [http://www.nist.gov/el/building_materials/resilience/research-center-help-communities-increase-resilience-to-disaster.cfm](http://www.nist.gov/el/building_materials/resilience/research-center-help-communities-increase-resilience-to-disaster.cfm) - the center 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.”

4) **U.S. Department of Homeland Security**
Presently in the final stages of creating the Critical Infrastructure Resilience Center of Excellence.

5) **Resilience Engineering Association**
According to the website - [http://www.resilience-engineering-association.org](http://www.resilience-engineering-association.org) - The REA has the following aims and programs:

**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.

6) **University of Tokyo**
According to the website - [http://rerc.t.u-tokyo.ac.jp/index_en.html](http://rerc.t.u-tokyo.ac.jp/index_en.html) - The Resilience Engineering Research Center (RERC) was established in April 2013 to promote research into the principles and methodologies for realizing resilient systems. The center 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.

7) 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 coordinated 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.

http://www.arcc-network.org.uk/about-arcc/
Appendix 3: Further Reading


Hollnagel, E, 2015: FRAM - the FUNCTIONAL RESONANCE ANALYSIS METHOD: modelling complex socio-technical systems