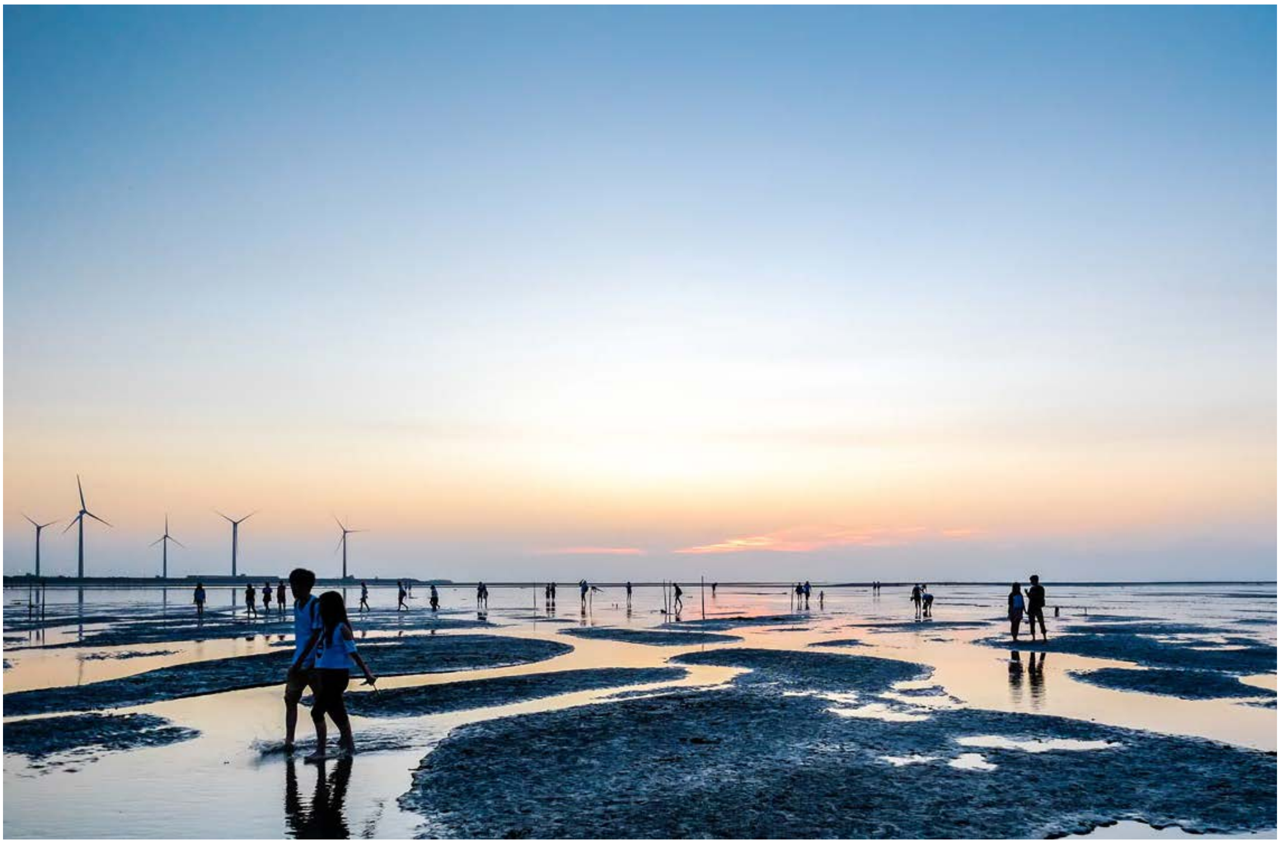
THE RESILIENCE SHIFT

Learning for Resilience and Complex Systems Thinking

Agenda Setting Scoping Studies Summary Report



Drafted by Roland Kupers and Mark Foden

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Executive summary

This video – Research Report Summary – summarises this report:

Introduction

Man can only act upon the nature, and appropriate her forces to his use by comprehending her laws.

Alexander von Humbold

The assumption in this report is that Resilience Engineering must embrace the science of complex systems. In this perspective critical infrastructure projects take account of the entire system that they are part of and have a capacity to adapt, evolve and transform (Walker 2006): No complexity, no resilience.

Engineering is of course no longer about strict linear optimization and there is a rich literature and practice on systems engineering. But this is often merely a richer characterization of a system, with more feedback loops and wider boundaries – but those systems are still closed and have finite states. This is very valuable in itself, but it is something leading edge companies like ARUP already know about. Resilience in the perspective of complex systems is broader than that.

One notable illustration is the Dutch "Room for the River". After a 50-year construction project to create a systemic defence against a quantifiable flooding threat, the Netherlands radically shifted gears to now deal with much less knowable climate change risks, characterized by heavy-tail risk profiles. Another illustration is Green Infrastructure such as artificial wetlands for wastewater processing. This has been the subject of a case study in 2014 with Dow Chemicals, Royal Dutch Shell and The Nature Conservancy (Kupers 2014).

Our approach to resilience focuses on engineering approaches to the tougher problem of resilience in complex systems, with open boundaries, heavy-tail risks and irreducible uncertainties. This requires a non-probabilistic approach (Chang et al 2014).

In this report we conduct a literature review on education for resilience engineering, review the current state and make recommendations for next steps.

Literature review

This section reviews literature related to Resilience Engineering education.

Introduction

Although much has been written on resilience, the connection to engineered systems is relatively new. A new Journal for Sustainable and Resilient Infrastructure from Taylor and Francis was, for example, launched in 2016. The focus of this report - education - is even less studied. A list of the literature consulted is in Appendix A.

In this section we extract some of the insights that pertain to our purpose of exploring learning for 'resilience engineering'.

Defining resilience

Resilience means different things in different disciplines and has evolved over time. For the purpose of this paper, we choose a definition of resilience in the context of complex adaptive systems. In essence this means that a system is both robust to stresses, and has the capacity to learn and adapt: resilience combines robustness and adaptive capacity.

CASE 1 – 'BUILDING WITH NATURE': THE SAND MOTOR

Every year, the sea takes sand from the Dutch coast. Every five years, Rijkswaterstaat replenishes the shortfall by depositing sand on the beaches and in the offshore area. Without this, the west of the Netherlands, which is below sea level, would be exposed to the sea. By building the Sand Motor on a peninsula on the coast, the aim was to find out whether the forces of nature can spread sand along the coast for us.

Between March 2011 and November 2011, the hook-shaped peninsula was created. It extends 1 km into the sea and is 2 km wide where it joins the shore. Trailing suction hopper dredgers picked up the sand ten kilometres off the coast and took it to the right place.

The Sand Motor is an example of building with nature. By depositing a large amount of sand in a single operation, we can avoid repeated disruption of the vulnerable seabed. Nature will take the sand to the right place for us. If the Sand Motor fulfills our expectations, sand replenishment off the Delfland Coast will not be required for the next 20 years. The Sand Motor is the first experiment of its kind. The vision is to work with water, instead of against it. Based on its success, similar projects are envisioned in Norfolk, UK and in Jamaica.

Scientists are studying how the Sand Motor develops to see whether this innovative method for coastal protection does indeed work. Measurement data are also needed to manage the Sand Motor properly. One example is mapping out new currents so it is known where it is safe to bathe. But also to see which animals visit the Sand Motor, and how visitors spend their leisure time on the Sand Motor. ....

The traditional definition of 'engineering resilience' is more limited and best described as robustness: "*bouncing back faster after stress, enduring greater stresses, and being disturbed less by a given amount of stress".* In many contexts this is what is colloquially meant by resilience, but we will refer to this aspect as 'robustness'. In engineering this is very familiar. A system such as a bridge or a building is in a state of equilibrium, which is disturbed by a stress such as a storm. Faced with this stress, the system is able to withstand it, return to its initial state and maintain its function. A significant limitation of this definition lies in the presumption of a stable equilibrium: "Children in poverty who overcome adversities do not stay the same, but they can still be seen as resilient" (Martin-Breen 2011).

Both the potential and the limitation of the idea of resilience for engineering, becomes apparent. The enormous success of the engineering discipline rests on the capacity to largely isolate a system from its surroundings; so that equilibrium is a reasonable description of its state. It is essentially a process of containment. The equilibrium is not static and engineered systems can respond to a vast array of variation. Take the wings of an airplane as an example. They are designed to withstand an enormous range of stress without losing their function and return to their original condition. This is clever engineering, but the system does not adapt to the circumstances – or learn. Similarly the long effort to develop nuclear fusion focused on the daunting ambition of containing an essentially chaotic process into a stable plasma, so that it can be exploited reliably. Robustness – or 'engineering resilience' – is very important and engineers have continuously improved their skills and ability to achieve this. This approach to engineering is based on the great success of the science of thermodynamics that describes systems as equilibrium states characterized by an extreme value of a potential function.

This is in contrast to the evolutionary process of the natural world, where systems continuously evolve. These are open systems – i.e. far from equilibrium. In these systems the power of potential functions that are optimized must be renounced. These insights formed the basis of the science of Complex Adaptive Systems, gradually building our knowledge and understanding of the emergence and adaptive processes that characterize them (Strengers 2004). In these open systems, resilience is not only the capacity of robustness, but also the capability to adapt. Although this is clearly relevant for natural and social systems, is it relevant for engineering?

CASE 2 – WEAVING RICKETY DAMS IN INDONESIA

Mangrove forests form natural coastal defences in Indonesia and elsewhere. The forests trap sediment both from the sea and from the rivers flowing into it.

Rickety-looking little dams woven from reeds catch sediment that the waves carry in from the sea. The water streams back through the semi-porous dams, while the sediment stays behind. This leaves a muddy nutrient base for mangrove recovery along the coast. The technique comes from the Netherlands where it was traditionally used for centuries. It became a standardized method in 1900 for Dutch infrastructure.

The dam project on Java started in the autumn of 2013. Already, four kilometers of dams have been constructed, each of them 100 metres long. The first results are impressive, according to water experts. In one and a half years the coastal strip has been raised 40 to 50 centimeters.

While elsewhere in the world governments and local people set to work to plant out cuttings and seedlings, those taking part in the Java project are waiting until the naturally floating seeds germinate of their own accord on the newly formed soil. The engineering is designed to assist natural forces to build infrastructure, rather than supplant them.

Adapted from Wageningen World no 1. 2017, page 28-32

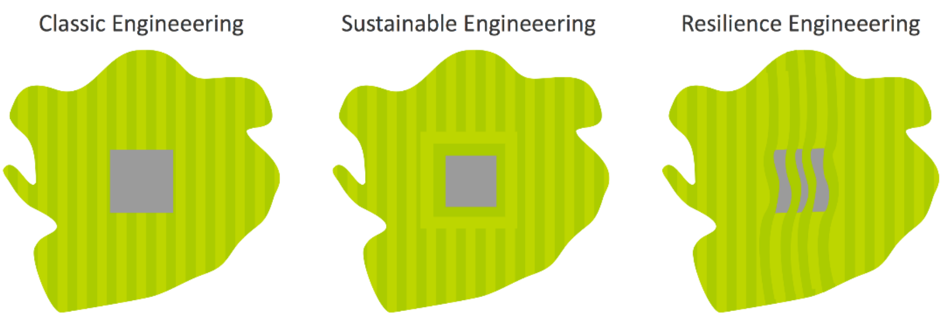
While many and perhaps most systems are well approximated by equilibrium, in critical cases this is insufficient. This is most apparent when the system itself is a complex adaptive system. The best clues can be found when there are many autonomous and heterogeneous agents, interacting intensely and building a highly interconnected dynamic system. Simple examples are traffic flows, but also modern cities are complex. "Resilient infrastructure systems are essential for cities to withstand and rapidly recover from natural and human-induced disasters, yet electric power, transportation, and other infrastructures are highly vulnerable and interdependent. New approaches for characterizing the resilience of sets of infrastructure systems are urgently needed, at community and regional scales." (Chang 2014).

It is worth noting that there is no inherent contradiction between engineering as a discipline and adaptation for resilience. Engineers are naturally inclined to solve problems pragmatically and adjust those solutions as required. However the manufacturing and project management requirement for engineering projects often drive towards rigidity. When the US was massively scaling up production of bombers during WW2, Henry Ford offered to build 1000 B-24 planes a day, provided the design was frozen was rejected by the military. But design changes from battlefield experience, material and labour shortages required constant improvisation. Roosevelt rejected the offer. The Ford factory at Willow Run continued to struggle to scale up B24 production, while production of the more complicated B17's at the Boeing factory in Seattle soared. Boeing's factories were adaptive and learning systems, while Ford's were not (Zeitlin 1995 and Mishina 1999).

A taxonomy of systems

A particular piece of engineered infrastructure may not be resilient as we have defined, in the sense that it is not capable of adaptation and learning. In practice that infrastructure may well be part of an infrastructure network that does constitute a complex system. Collectively the infrastructure its global behaviour cannot be easily described in terms of distributed local actions. For example the City of Surat built a dam to help control the frequent flooding of the city, as well as provide power to an energy deficient urban environment. However if the dam is optimized for power production, by allowing its reservoir to be filled, it will lose its capacity for absorbing sudden water surges. These kinds of trade-offs are simple examples of the consequences of interconnecting infrastructure.

To classify the approaches to teaching 'resilience engineering' we introduce a model. The model describes three types of infrastructure engineering. The grey represents infrastructure and the greens the context or system that it is in. The shades of green represent the contrast between natural and societal systems:



1. Classic engineering – where the infrastructure is designed according to a fixed specification.

2. Sustainability engineering – where the interconnection of a classically engineered system with its social and natural environment is considered. One can consider the resilience of the system as a whole. This marginally engages the engineering discipline, but is mostly about governance, ecological considerations and stakeholder engagement. In many ways this overlaps with the almost traditional sustainability approach of the past decades.

3. Resilience engineering – where the infrastructure itself is adaptable with its context, both societal and natural. This can be either through individual engineered systems that is resilient in itself. The engineered system itself has adaptive properties, in addition to mere robustness. In the interaction with its social and natural environment, the system changes and evolves. A variation is where there may be a network of classically engineered systems (such as in a power network), and one considers the dynamics of the system as a whole. The adaptability comes from the management and interconnection of infrastructure pieces, rather than from the adaptability of the individual asset.

CASE 3 – 'GREEN INFRASTRUCTURE': THE SHELL/DOW/TNC CASE

Green Infrastructure (GI) refers to engineered infrastructure that uses the principles of nature to perform its functions. Prime examples are artificial wetlands or reed beds for the treatment of waster waters from industrial operations. Turbulence (2014) contains case studies from Dow and Shell, written in partnership with The Nature Conservancy. It lists ten examples of the implementation of GI in various parts of the world and different companies, it describes the business case for GI and most interesting reflects on the barriers to implementing and scaling such solutions.

Turbulence (2014) defines GI as follows: "GI solutions are defined, for the purpose of this study, as planned and managed natural and semi-natural systems which can provide more categories of benefits, when compared to traditional gray infrastructure. GI solutions aim to build upon the success that nature has had in evolving systems that are inherently sustainable and resilient. GI solutions employ ecosystem services to create more resource-efficient systems involving water, air and land use. GI solutions are designed to fulfil a specific need, such as water purification or carbon sequestration, while often offering location-specific and valuable co-benefits, such as enhanced habitat for wildlife."

CASE 3 – ‘Green Infrastructure’: The Shell/Dow/TNC case (continued)

For each of the cases the financial, and the other co-benefits as well as the disadvantages are listed. Inevitably in many cases the projects are optimized in hybrid solutions, which contain elements of Green and Gray Infrastructure. A table looks at the generic advantages of Gray versus Green. There are substantial differences in dimensions such as footprint, operating cost, susceptibility to external factors as well as monitoring and control. In many cases the business case for Green is much better than for Grey infrastructure, with of both lower initial capital expenses and ongoing operational and maintenance expenses.

However in practice these solutions don’t scale beyond successful pilots. “It’s hard to sell a swamp to an engineer”, was a key message from one of the project team. Notwithstanding an often-convincing business case, Green Infrastructure runs to the core engineering practices of many firms. They are not blueprint driven and continue to evolve during the operation phase; the standard stage gates of project management of design, construction and operational phases do not apply in the same way.

Turbulence (2014) concludes, “Leadership emphasis and change management is required for successful implementation. Through whatever combination of resources and expertise, organisations are advised to build a fit-for-purpose set of capabilities integrating the areas of strategy, innovation, new business development, project economics, engineering and environmental sustainability.” These lessons are an important consideration for the broader resilience engineering discussion.

Review of the current state of resilience in engineering education

This section sets out the method and findings of our research.

Method

We interviewed experts and reviewed curriculum descriptions on institution websites.

Expert interviews

We interviewed six complexity and resilience experts who work at universities or are otherwise involved with engineering education.

The interview protocol and list of interviewees are in Appendix B of the complete report. The interviews were confidential so the content of the discussions is integrated into our findings.

Website review

We identified the top engineering institutions and reviewed their websites. Using the QS University Ranking of engineering schools, 21 were selected for relevance of the idea of 'resilience engineering'. Of these, 14 were in the top 20 schools worldwide; an additional 7 schools were selected for regional diversity or because they were seen to be potential champions in the field.

The following steps were followed to populate the table contained in Appendix C of the complete report:

- Observations on outcome of search for "resilience engineering"
- Observations on outcome of searches for "complexity" "complex systems" "resilience"
- List relevant courses and observations
- List relevant departments and URLs
- List relevant faculty members and observations
- Other observations

We acknowledge the limitations of a website-based search and obviously this consists of this a first tour d'horizon, rather than an exhaustive ranking of schools.

Education maturity

We developed a 1-5 scale to classify the maturity of education related to resilience engineering:

1. Schools in the Classic Engineering frame – those focusing on engineering robustness to dynamic stresses. Most are in this category.

2. Schools in the Sustainable Engineering frame - those acknowledging that connecting environment, sustainability and engineering is important - and offer combined courses (like Stanford).

3. Schools that have separate complexity institutes that look at system resilience - but are really not connected to the engineering discipline.

4. Schools approaching the Resilience Engineering frame – those that offer selected courses integrating complexity, resilience and engineering

5. Schools in the Resilience Engineering frame – those that make resilience engineering part and parcel of their engineering curriculum.

Findings

Of the institutions we looked at we identified six that scored a 3 on our maturity scale, three that scored a 4 and none that scored a 5. The expert interviews have also confirmed our findings of the paucity of 'resilience engineering' education and they have also not yielded any new education programs that we had missed.

These six schools scored 3 on our metric:

UNIVERSITY OF CAMBRIDGE Stanford University ETH Zürich

Several schools have a strong focus on sustainability. Examples are KTH in Stockholm and Harvard. This focus generally pertains to 'sustainability engineering' - the connection of an engineering system to its environment, rather than designing new systems that are robust and adaptive per our definition.

The following three institutions scored a 4 in our ranking. While many more schools organized conferences, workshops or had specific research programmes, only these schools additionally evidenced some level integration into the standard curriculum by offering dedicated courses:

The following four courses stood out:

- Engineering: Building with nature offered by TU Delft on edX. It aims to teach how to use ecological and engineering design principles to develop more effective and sustainable hydraulic infrastructure.

- Transdisciplinary Education Program on Resilience Engineering at Tokyo University. This is part of a long-standing effort to build purposefully cross-disciplinary programs for an engineering approach that looks at resilience that includes not only the responsiveness to abrupt disasters or crises but also the ability of a system to adapt itself.

- The Systems Program at Berkeley.

- Fraunhofer academy offers A 6 semester course Diploma of Advanced Studies (DAS) »Resilience Engineering« is offered. It consists largely of specified resilience response, looking at flexible and efficient solutions to identified threats. It does not reach to general resilience and system adaptability in complex systems. A 1-semester course Certificate of Advanced Studies »Resilience analysis« has started in 2017, with a strong focus on analysis and metrics for resilience assessment for specified resilience.

Some characteristics of the schools that were ranked lower on the scale:

- Maturity Level 3 schools - Several other schools had Institutes with a comprehensive interest in resilience and attention to the impact of complex systems, but these were not connected to the engineering curriculum in their institutions. Examples are the Complexity

Institute at NTU Singapore or the James Martin Institute for the 21st Century in Oxford. The MIT Sloane School is the home of Systems Dynamics, a precursor to the science of complex systems and is also not visibly integrated with the engineering departments at MIT.

- Risk/Safety approaches - Others evidenced an interest in the resilience of engineering systems, but purely from a risk management perspective, rather than an infrastructure design point of view. Examples are the Engineering Risk Analysis Group at the Technical University Munich. These are part of Maturity Level 1.

Key gaps

As discussed above Resilience Engineering thinking is beginning to find its way into engineering education but is still at an early stage. There are some centres where thinking is well developed and, more widely, research is increasing; however there is little formal teaching provided on engineering courses.

It’s clear from our conversations that Resilience Engineering is as much a political, economic and social issue, as it is an engineering one. To enable useful change it’s important for students of these other fields – like economics, politics or management - to learn about resilience as well as those in engineering

Since systemic resilience approaches involve substantial change in mindset and have potentially significant long-term consequences, change is likely to take many years. It will be important to enable the whole system to learn. This means both educating students and promoting learning amongst practitioners at all levels (particularly the most senior).

Resilience Engineering is immature. Change in the education sector is likely to be complex and messy. Early work on promoting change must take this into account. It’s important to grow connections between people and to enable new meaning to emerge; perhaps through active collaboration on projects across industry and academia.

Our research and the expert interviews highlighted three important gaps:

1. Educational material – both for engineers and for those who commission their work
2. A community-building mechanism
3. A common language

In section 4 we discuss recommendations in each of these areas

Language

There is diverse language around the concept of resilience engineering, such as ‘Resilience Engineering’ itself, ‘Building with Nature’, ‘Green Infrastructure’ or ‘Resilience by Design’. All of them refer to complexity as the underlying systemic approach, although none has coined the term 'complexity engineering'.

If we could express a mild preference, it would be for 'building with nature'. It clearly states that the focus is on "building" as contrasted to risk management, stakeholder engagement, ecosystem compatibility etc…; "nature" expresses a methodology that takes its cue from the organizational principles of nature; "with" describes the connection, but helps contrast with biomimicry which copies a design in nature, rather than integrate selected natural principles. This is term championed by the TU Delft and its edX courses.

However in this nascent field, there are disadvantages to picking a label too early lest it close off areas of investigation in an unforeseen way. Our recommendation would be loosely carry multiple terms. Our expert interviews confirmed that they would be comfortable and indeed recommend such an approach.

Conclusion

The discipline of Resilience Engineering as defined in the previous segment is clearly not (yet) anywhere close to mainstream across the global engineering schools. There are several universities that have the ingredients such complexity, sustainability, ecological systems or resilience risk management, but very few have put these ingredients together into a curriculum.

Recommendations

We have three recommendations:

Learning

Universities will likely continue to develop educational programs as the field gains momentum. The obvious route for the Resilience Shift project is to connect with the Universities identified above and catalyse the development of further educational programs inside engineering schools. This can be accomplished by connecting early champions with potential early followers, for example through workshop sessions to engage and connect the educators. The Resilience Shift website can be a live catalogue for good practice around the world.

However at this early stage there is real value in having a focused set of educational material owned and developed by the Resilience Shift that can serve as a catalyst, both with engineers and with the people commissioning and governing engineering projects.

Community building

Resilience Engineering represents a profound change in the way that critical infrastructure is created and used. It is important to approach this change as an influencing of a complex system rather than an engineering-style implementation project. The Resilience Shift must: think big, start small and move fast; it must be the change it wishes to see.

This would be facilitated using state of the art techniques such as un-conferences, world cafes etc.. Outcomes could be reported either in text of video format and published on the Resilience Shift sponsored community website. The need and importance of this has been confirmed in several of the expert interviews.

Language

As the Resilience Shift project develops it should remain open to different language for the field – and ideally catalyse a consensus between the champions. A common reference is obviously helpful, as it helps people with shared interest find each other. Diversity can be useful in the early stages to foster recombination and new ideas.

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   2. Ability to monitor incoming critical situations
   3. Ability to anticipate the occurance of future events
   4. Ability to learn from the past

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   Engineering Resilience - Maintaining system form - eg bridge withstanding various loads

   Systemic Resilience - Maintaining system function - eg local inhabitants replace failing bridge with ferry service

   Adaptive Resilience - Adapting system function - eg local inhabitants use video conferencing to communicate with others on the other side of the bridge

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