Beyond the boundaries: characterising situational uncertainty in complex systems

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Executive summary: In today's interconnected and dynamic socio-technical systems, what is not being seen beyond perceived boundaries–situational uncertainties–can prove to be even more important than what is seen or imagined. Failing to recognise and acknowledge situational uncertainties can lead to flawed judgements by decision makers and potential catastrophe. But, as various examples show, the necessary knowledge often exists but remains unrecognised. Identifying these "unknown knowns" offers an immediate opportunity for enabling safer complex systems.

Tags: socio-technical systems, complex systems boundaries, postnormal science, knowledge gaps, flawed decision-making, situational uncertainty, unknown known, sense making, scenarios, storytelling

Section 1: Background and introduction

Waldseemüller's Admiral's Map (**Figure 1**), published in 1513, is one of the earliest maps of the Americas. At that time, South America remained unexplored. It was marked '*Terra Incognita*' (unknown territory). As they journeyed beyond the boundaries of the known world, into those unknown areas, explorers knew that they had to proceed with caution.

This case study considers a modern-day equivalent. How do the decision-makers that manage complex systems recognise and acknowledge when limits of knowledge and methods are being approached? Do they understand the implications of not doing so?

These questions matter. Although established methods for managing system risks are generally effective, they rely on the ability to see (or imagine) the uncertainties involved. These methods address 'known unknowns'. As mediaeval mapmakers recognised, explicitly recognising and communicating the 'unknowns', the limits of our knowledge, is just as important as sharing the "'knowns', what is known. Having an illusion of knowledge can lull us into a false sense of security and is particularly dangerous.[2]

In addition, complex systems are fundamentally different to complicated ones. Previously successful analytical, scientific, risk-management and regulatory practices are being over-extended by the systemic risks of our complex, contradictory and chaotic world.[3] That creates new challenges for risk assessment and risk governance.[4] As disruptive events become more commonplace[i], it becomes ever more important to be aware of uncertainties and the nature of the system being faced.

A specific issue is that many of the complexities of today's highly interconnected socio-technical systems arise at boundaries between systems, or parts of systems. Past failures show how perceptions about such boundaries can obscure emerging issues or risks. 'Situational uncertainties', our term for knowledge gaps beyond perceived boundaries, can lead to flawed judgments. They can hinder the ability to anticipate complex system behaviours and then mitigate risks.

This case seeks to raise awareness of boundary issues in complex systems. It uses a variety of illustrative examples to draw these out, broadly characterising situational uncertainty into three typologies (myopic, accidental and disjointed). Although not mutually exclusive, each type has distinct challenges to be addressed.

In particular, we highlight the considerable potential for making better use of knowledge that exists but is not shared: the 'unknown knowns'. This gives policy- and decision-makers an immediate opportunity for addressing situational uncertainty and enabling Safer Complex Systems.

The case is based on a longer report[5] that explores the issues in more detail. This report includes setting out the fundamental differences between complex and complicated systems, outlining possible responses for tackling situational uncertainties and contextualising this within the broader demands of navigating complex systems in an increasingly disruptive world.

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Figure 1: The Admiral's Map—published 1513[1]

Section 2: Analysis and insights

Complex systems failures: boundary issues

Complex systems rarely have obvious boundaries. As Meadows[6] put it: "Everything, as they say, is connected to everything else, and not neatly. There is no clearly determinable boundary between the sea and the land, between sociology and anthropology, between an automobile's exhaust and your nose. There are only boundaries of word, thought, perception, and social agreement—artificial, mental-model boundaries. The greatest complexities arise exactly at boundaries."

While, in principle, system boundaries should be defined by their purpose (or the problem to be solved), this is not straightforward. The concept of 'inside' and 'outside' a system is never simple or uncontested. A desire to reduce a problem to manageable proportions can lead to a system being defined less by its purpose and more by its physical, organisational, or geographic domains—which may obscure the issues and complexities at play.[7] This can then be compounded by changes over time; by behavioural influences such as cognitive or social dynamics that affect information flows; or by an individual's view that affects how a system's purpose may be perceived.

The ways in which boundaries are perceived affect the degree to which uncertainties are recognised and addressed, or not, by key players—potentially resulting in complex system failure.

Beyond the boundaries: situational uncertainty

We defined the term 'situational uncertainty' to reflect the imperfect, unknown, or unimagined information that lies beyond a perceived boundary and that therefore often remains unrecognised. This distinguishes it from recognised uncertainty ('known unknown') within, or closely linked to, a system, which can be surfaced and subsequently managed through typical risk management processes.

Sometimes, situational uncertainties may reflect factors or influences that are beyond the limits of anyone's knowledge: the truly 'unknown unknowns'; those things that 'we don't know that we don't know' until they emerge at pace to surprise us.

However, all too often these are actually 'unknown knowns'. That is, some people or groups see the signals of imminent issues, or hold information that could avert or mitigate a major failure, but this is not seen or not acted upon by decision-makers.

Part of the issue, according to Taleb's work on 'black swans'7[7], is that humans are hardwired to learn specifics when they should be focused on generalities. Because we tend to concentrate on things that are already known, time and time again there is insufficient effort made to consider what is not known. Humans are vulnerable to the impulse to simplify, narrate and categorise and not open enough to rewarding those who can imagine the 'impossible'.

This highlights an obvious vulnerability for the safety of complex systems: unless people recognise and communicate a particular uncertainty, it will not be assessed or acted upon. Uncovering what we do not know, but that is already known somewhere, could go a long way to avoiding or mitigating system failures.

Characterising situational uncertainties

Three broad types of system failure, attributable to perceived boundaries, have been identified in this work: myopic, accidental and disjointed (**Figure 2**). Illustrative examples are set out below.

In practice, a system failure may involve more than one typology, so they are not mutually exclusive. However, each type has distinct challenges to be addressed. The typologies reflect the wide range of examples examined, but we note that additional types may emerge in the future.

The myopic system

Near sighted (myopic) perspectives can take many forms. The following examples illustrate issues that can arise when geo-political, social and natural contexts are not sufficiently taken into account:

- Geo-political influences: more than 600 dams have been built in Iran since 1979, with the aim of managing water for agricultural, industrial and domestic uses, generating 'green' power from hydroelectricity and supporting economic development.

  Yet, whatever their intended local benefits, these dams have negatively influenced ecological, social justice and geo-political systems that lie well beyond their immediate boundaries. Water shortages have prompted deadly protests in the Khuzestan province as communities[8] question why 'their' water must be transferred to other regions while they suffer from thirst. Downstream of the Iranian dams, in Iraq, changed water flows in the Tigris and its tributaries damage an economic lifeline in an arid region and raise the spectre of 'water wars' (which is compounded by major new Turkish dams impacting the Tigris-Euphrates basin).

- Cultural influences: the Bhopal disaster in 1984 led to an official death toll exceeding 5,000 and more than half a million people poisoned as toxic gas leaked from a pesticide production plant.

  This resulted from the combination and accumulation of many factors, including failure to acknowledge the cultural differences that existed. Bhopal was operated by an Indian subsidiary of an American multinational (Union Carbide), each with a vastly different understanding of risk, regulation and responsibility.[9] Practices that might be acceptable for US operations failed to account for the Indian plant being sited in a dense urban region and operated by a less skilled workforce. After the disaster, further cultural disconnects played out in the conflicts between key actors, their differing communication objectives, and media reactions, all of which shaped wider responses to the tragedy.[10] Long-drawn out judicial processes exacerbated the impact on victims and highlighted the power asymmetries at play.[11]

- Natural-hazard triggered technological (Natech[12]) accidents: the Fukushima Daiichi nuclear power plant meltdown was triggered by the cataclysmic Great East Japan Earthquake and Tsunami of 2011.

  While Natech accidents are often claimed as 'act of god' events, all too often they result from inadequate assessment or preparation for the challenging natural environments to which a plant may be exposed.[13] The investigation into Fukushima[14]

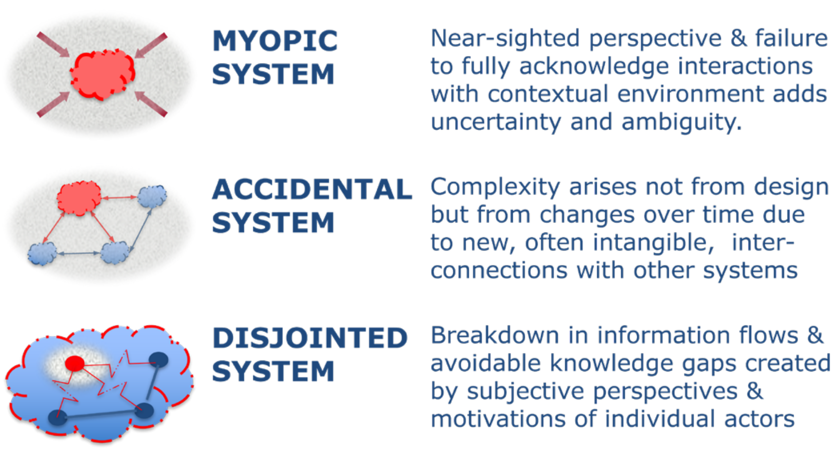

Figure 2: Typologies of boundary failures in complex systems

concluded that it resulted from poor design assumptions, faulty decision-making and complacency that led to insufficient awareness of the obvious dangers of siting hazardous facilities on a tsunami-prone coast. It was described as an organisational and governance failure: "a profoundly manmade disaster—that could and should have been foreseen and prevented."

The accidental system

The following examples illustrate the issues that can arise from new interconnections or other (un-designed) additions and changes over time, which significantly alter the nature of the system:

- Interdependencies between infrastructures: in August 2019, a power outage triggered by a lightning strike affected more than a million users in England. Failure in the electricity transmission system then rapidly cascaded to other infrastructures, significantly disrupting essential rail services, hospitals, water supplies, oil refineries, and airports.

  Over the past decade, there have been significant changes to the UK's generation mix. It has moved to include a greater amount of electricity generation from many smaller generators connected to the distribution network. Reviews of the incident[15] highlighted potential mismatches between the operational practices, software and design codes developed for a largely centralised electricity generation system and those now needed by an increasingly distributed network. Added complexity was introduced by the need to blend fundamentally different innovative technologies with legacy systems and processes.

- Shared dependencies: a maritime trial by the General Lighthouse Authorities of the UK and Ireland, working with the UK Ministry of Defence, tested what happens when Global Positioning System (GPS) fails at sea.[16] It highlighted wide ranging impacts. Simultaneous alarms as GPS- dependent systems failed overwhelmed crews, conflicting information created confusion on shore and critical safety systems were compromised.

  The use of GPS has become commonplace in data networks, financial systems, shipping and air transport systems, agriculture, railways and emergency services. With a surprising number of different systems having GPS as a shared dependency, a failure of GPS could lead to the simultaneous failure of many critical infrastructures and services that are assumed to be independent of each other. Although seemingly improbable, a repeat of the massive 1921 solar super-storm, which disrupted the earth's magnetic field and caused pandemonium to communication systems around the globe, could be devastating.

- Critical transport nodes: the organisation of global transport infrastructure around several highly connected nodes (such as Chicago's O'Hare International Airport, London's Heathrow Airport and the Suez Canal) has created points of potential systemic instability.

  These highly connected nodes have developed and become increasingly important over time. This is closely linked to the evolution of the 'just in time' supply chains that make use of them. When the Ever Given container ship became stuck in the Suez Canal in March 2021—blocking it to all other traffic for six days—it affected the global shipping industry and countless businesses, from domestic transport providers to retailers, supermarkets and manufacturers that rely on delivery of supplies. Cost estimates run into the billions of dollars. It showed how a single shock affecting these critical nodes can escalate rapidly to cause widespread issues.

The disjointed system

The following examples illustrate issues that can arise from disconnects and ineffective information flows across interfaces (functional boundaries) within the system:

- Limited professional (or institutional) lenses: the British Academy's explanation of why no-one saw the 2008 financial crash coming[17] summarised that: "The failure to foresee the timing, extent and severity of the crisis and to head it off, while it had many causes, was principally a failure of the collective imagination of many bright people, both in this country and internationally, to understand the risks to the system as a whole."

  Looking at the system through a single (disciplinary) lens may result in the whole system being framed in a way that reflects a lack of awareness that important things have been left out. In this case, there were many warnings about imbalances in the financial markets and in the global economy. But, standing against those, was the dominant belief in the professional expertise of the bankers and their wizardry in creating new ways of mitigating the risks. A desire to believe drowned out the conflicting views and the inconvenient facts.

- Piecemeal additions to regulatory systems: these can result in multiple regulators becoming involved—each with their own jurisdiction and institutional interests—which can lead to gaps, overlaps and inconsistencies and reduced regulatory effectiveness over time. Tragically, this type of issue led to 72 lives being lost in the

Grenfell Tower fire in London in 2017.

The subsequent review of the UK's building and fire regulations[18] drew out how ignorance and indifference, coupled with lax enforcement and insufficient accountability in a fragmented industry, had created a culture that undermined building and fire safety. Interface issues and gaps across the regulatory system left plenty of scope for shortcuts and non-compliance. In this case it was compounded by the fact that the concerns of residents were not adequately listened to and things became progressively worse as trust in the institutions involved became increasingly eroded. The ensuing catastrophe, yet again, highlighted systemic failures to learn from previous events.[19]

- Concealed risks: the wrongful prosecutions of thousands of sub-postmasters in the UK shows how concealment of information can pervert justice over two decades and ruin very many lives.[20] Sub-postmasters were convicted and sentenced for fraud on the basis that computer system data must be correct, when in fact there could be no confidence that the data was reliable.[21] It showed how humans, with a 'computer never lies' mentality, can blindly accept the output of automated systems as reliable evidence.

  The legal case[21] also showed how serious concerns about data reliability was not shared, despite being known within the organisations. 'Uncomfortable knowledge' may have been subconsciously or deliberately concealed, an example of how ignorance can be seen as a positive achievement.[22] Ultimately the implications go much wider: the trustworthiness of institutions relied on by society was seriously undermined.

Boundary issue: summary

The brief examples of the myopic, accidental, and disjointed typologies described above illustrate how the perception of boundaries (at whole-of-system or functional levels) influences the way in which complex systems and their associated uncertainties are understood.

Failing to recognise related uncertainties, and hence operating with an illusion of knowledge, can lead to important signals of imminent failures being missed and actions being taken that escalate rather than manage the issues. The insights generated by these examples raise a number of generic points about boundary issues that require attention when designing or assuring complex systems:

- Specifying where a boundary lies is rarely obvious. For example, should the boundaries be drawn around a major dam and its immediate impacts, or extended to cover the significant geo-political or social justice systems that the dam forms part of? How should natural systems be accounted for and to what extent should factors influencing these be incorporated into the system?

  Boundaries do not need to represent some spatial arrangement: its components can be both tangible and intangible and may exist in completely different spaces (such as different geographies), or even be virtual (such as data networks, with computers being the actors).

- How complex systems are defined and perceived depends on the lens they are seen through and how different actors interpret the intended purpose. These perceptions can be reinforced by the language used to describe the system or its behaviours. There can be many different, but each equally legitimate, views.

  When a biologist looks at a forest they may focus on the ecosystem, an environmental activist on the impact of climate change, a forester on the state of tree growth, a business person on the value of the land. None are wrong, but none describe the entirety of the forest system. These partial views can lead to designs that embed conflicting objectives and drive unintended behaviours within the system. They can create serious ambiguities.

- Decisions on where to place the boundary, and what to include within it, will depend on who is analysing the system and for what purpose (or for what problem to be solved). It will tend to be subjective and pragmatic, determined by what is seen as the system's purpose (or problem to be solved) and often defined at a specific point in time. In any case, the inherent assumptions need to be explicitly acknowledged.

  In simplifying the system to a level that can be analysed or managed, it is easy to lose sight of its contextual environment and hence limit awareness of important developments happening across and beyond the system boundary. Associated issues can be amplified by failing to recognise or acknowledge the different cultures (and all the implications of those differences) which may be involved, as seen in the aftermath to Bhopal.

- Boundaries can and will change over time. The introduction of distributed electricity generation capabilities fundamentally changed electricity transmission systems. Widespread adoption of GPS applications or critical infrastructure nodes created single points of failure.

  Many systems that are not initially envisaged as complex can become so as their interconnections grow. What starts as a discrete and well bounded system can become part of some broader 'system of systems', or its components may form part of multiple systems, simultaneously.

- While the system boundary is generally considered as the 'perimeter' of the system, there can also be functional boundaries around individual actors or subsystems (primarily linked to function, behaviours or information flows). The decisions of individual actors within these functional boundaries can shape events that then play out in unexpected ways across the system.

  Note that the issue is not simply a decision maker's own beliefs, but also how they perceive other people's beliefs. That interaction influences the dynamics of relationships across the system. These perspectives, motivations and self-interests, all to some extent subjective, may ultimately result (deliberately or otherwise) in uncomfortable knowledge and uncertainty being airbrushed out. Underlying gaps in information or understanding often only become apparent after the event.

- While it is useful for decision makers to consider the sources of uncertainties characterised by these typologies, in practice these differences will not always be easily distinguishable.

  For example, a review of how uncertainties about the dangers of tremors felt ahead of the L'Aquila earthquake were communicated to the public[23] highlighted the multi-dimensional and dynamic nature of the uncertainties. Alongside the scientific assumptions and unknowns, there were also other uncertainties linked to multiple (conflicting) ethical, political, or societal perspectives. The review showed the contradictions and conflicts that arose as these different forms of uncertainty interacted. This kind of complexity poses particular challenges to the engineering community.

The previously described typologies, summarised in **Table 1**, highlight potential sources of uncertainty linked to boundaries. The table includes questions that might be asked by decision makers, or those assuring the performance of complex systems, to raise awareness of these potential uncertainties.

Appendix A provides an overview of approaches that may help in unearthing such knowledge (in particular, the unknown knowns) and in generating value from different perspectives in ways that may offer useful and novel insights.

Section 3: Discussion and transferable learnings

Navigating the multi-dimensional challenges, pace and uncertainties of disruptive worlds relies on capabilities to anticipate and to adapt.[24] However, the requisite levels of agility are rarely found in established institutional frameworks. There is often a low tolerance for uncertainty despite the need to embrace it: yesterday's safer complex systems will almost certainly not be those of tomorrow. Overcoming this inertia will be essential if we are to achieve safer complex systems in societies that are themselves rapidly becoming more complex and ambiguous. Without anticipation, we are navigating blind in an increasingly fast-paced uncertain world. Without adaptation, we are likely to respond ineffectively and too late. Now is the time to invest in smart choices that enable us to remain vigilant to the uncertainties and ready to take meaningful action in real time as necessary.

No new approaches are likely to be adopted without first developing a collective understanding of the threats and opportunities. This case study highlights how boundary issues can play out in complex systems. There are two dimensions that are recommended for early attention:

- Recognising complex systems as fundamentally different to complicated ones. Without that understanding, and an associated shift in mental models, it will be exceptionally challenging to get 'situational uncertainties' acted upon. A resource limited project will not readily switch effort from tackling 'known' issues onto considering what is not known: yet in a complex system that may be where the greatest risks lie.
- Recognising and acknowledging that what is <u>not</u> seen or imagined beyond perceived boundaries—the unrecognised uncertainties—can prove to be even more important than what is. The examples in this case illustrate what can happen when this is not done. Alongside listening to answers that may reduce levels of uncertainty, we must also pay even more attention to those questions that give us pause for thought.

This calls for education and communication materials that can build awareness through practical examples. Not all issues will be complex, therefore it is crucial to establish indicators that allow decision makers to differentiate between the many straightforward issues where established methods can work well and those disruptive ones with radically different demands.

The overriding message that we need to get across to policy makers and other decision makers is:

> *To achieve our goal of safer complex systems, whatever our track record, the most important part of our task may be recognising and remembering where the hard limits of our knowledge and analytical methods lie. This is a task that calls for on-going vigilance in a rapidly changing environment. In doing that, we need to*

SYSTEM BOUNDARY ISSUES		
Typology	**Illustrative uncertainties**	**Potential questions**
The Myopic System		
Critical issues may be evident, and recognised by others, in the contextual environment that lies beyond the system boundaries. Failing to look beyond perceived boundaries can blind decision makers to the full implications of their choices.	The cases showed how insufficient appreciation by decision makers of the contextual environment missed the impacts of other physical, natural, or social systems. Cultural disconnects resulted in failures to appreciate shifting societal attitudes and values, or trans-boundary (geo-political) effects.	• Who defined the system and its boundaries? How might different people view them? • When were they defined—has the system's purpose changed over time? • What is the system's sensitivity to changes in boundaries, uncertainties, or external events?
The Accidental System		
The introduction of new interconnections may fundamentally shift system dynamics. A short-term focus can create issues by failing to acknowledge latent risks, or long-term developments that could work via more indirect pathways.	The cases showed how intangible changes, some occurring imperceptibly over time, led to issues escalating in unexpected ways and at a pace that was previously unforeseen. Growing reliance on digital networks, data or other technological developments created unrecognised dependence on, or connections to, other systems. (In effect, this is an un-designed system of systems.)	• When was the system defined and what has subsequently changed? • What is the structure of the system—networked or linear? If networked, what network type and where are the nodes? • Where are the breakpoints and expansion points in the system? To what extent can they contain any disturbances in the system?
The Disjointed System		
The subjective perspectives and behaviours of individual actors or organisations can drive behaviours at a functional level to create barriers (which could be either inadvertent or deliberate) to information flows and knowledge sharing. That creates further uncertainties in how relationships within the system work in practice.	The cases showed how barriers at functional boundaries within the system can create knowledge gaps that lead to significant issues. Examples included institutions withholding information (including between themselves) for bureaucratic or other cultural reasons; and concerns about future personal or organisational consequences (reflecting power dynamics, legal liabilities or values). It can extend to intellectual property, commercial, or privacy issues.	• Whose voices are perceived as legitimate and heard—and whose are excluded? • Where can 'whistleblowers' or those who challenge the status quo find a safe space to engage in dialogue or ask relevant questions? • What assumptions are being made about risk transfer across a system? Are these credible?

Table 1: Overview of system boundary issues

capitalise on the insights and information provided by others. Complex systems do not respect boundaries—they cannot be tackled in silos.

Appendix A: Tackling Situational Uncertainty

We have set out the three broad types of system failure attributable to uncertainties obscured by perceived boundaries (.e. myopic, accidental, and disjointed). How can these situational uncertainties be addressed?

First and foremost, it requires a focus on a whole-of-system perspective, but this in itself is insufficient—there has to be a collective understanding of the issues, which means that the diverse insights that bring different perspectives on that system need to be shared.

Our proposed approach is set out in **Figure 3**, and described more fully within our research report.5 It involves working with communities to surface unknown knowns through three inter-related elements:

- sense-making: so that decision makers recognise the potential issues and contradictions that lie beyond their boundaries
- conveying uncertainty: to raise awareness among other actors of the issues and their implications
- taking action: to mitigate these uncertainties and associated system risks

The underlying purpose of this approach is to surface 'unknown knowns', hence the need for the collective. Once these 'unknown knowns' are recognised, they can be acknowledged and acted upon by decision makers as 'known unknowns'. However, due to the interconnected nature of the world we now live in and the risks we face, there is a need to repeat this cyclical process, on an on-going basis, each time tracking changes to the system, its dynamics and its contextual environment to ensure its continuing integrity.

The outlined approaches are more of an exploratory art than a predictive science and this may call for new capabilities. They also need to be context specific. In practice, the resourcing demands will also have to be kept proportionate to remain useful. The approaches also assume that there will be sufficient time and a shared ambition to invest in these methods which, for example under crisis conditions, may not be possible. Ultimately, it will come back to the purpose of the system and the decisions (or problems) that are being considered.

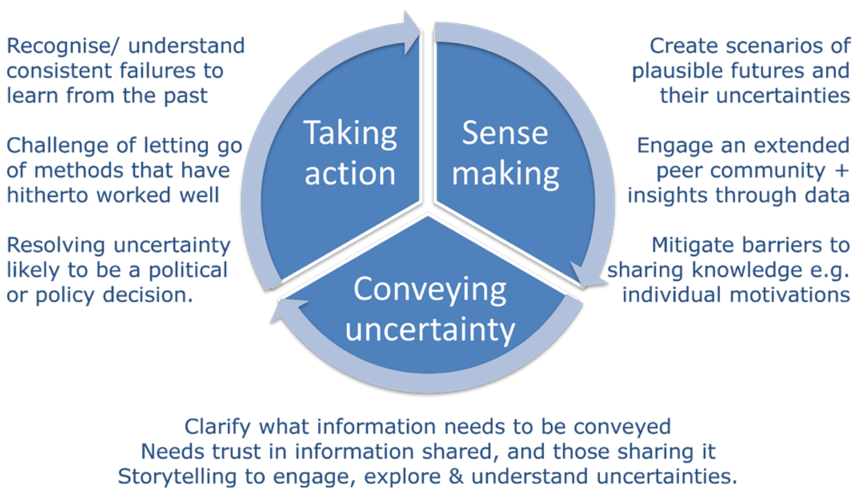

Figure 3: Tackling situational uncertainty

Implementation will not be straightforward. Navigating uncertainty in disruptive worlds calls for mental models, approaches and leadership styles that reflect the need to anticipate and adapt, crucially underpinned by trust. This requires awareness of the issues to reinforce capabilities that support:

- Preparing for disruptive conditions: approaches such as scenarios and storytelling offer options for developing our 'memories of the future', for putting in place early warning and other data collection mechanisms, and for explicitly acknowledging the uncertainties involved.
- Investing in relationships and deliberative mechanisms: building shared language and applying those decision science methods that can bridge disciplinary expertise and respectfully engage an 'extended peer community' (individuals with a direct interest in system outcomes, who may not have the 'usual' professional or academic background).

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Endnotes

i. Examples include: the COVID pandemic; the catastrophic floods across Western Europe and China, as the impacts of a changing climate play out; the Ever Given container ship getting stuck in the Suez Canal, to cause chaos with just in time supply chains; the cybercrime attack on the Colonial pipeline in the US. These events often involve issues and behaviours characterised by complexity, deep uncertainty, extreme pace and competing views, analyses and solutions.

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