Beyond the limits of knowledge: navigating 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.

Contents

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

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Foreword

Waldseemüller's "Admiral's Map", 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 report 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 (the "border with ignorance" [1])? Do they understand the implications of not doing so?

This report takes the reader on a journey to explore:

- What types of uncertainties exist beyond perceived boundaries in complex systems?
- How might these uncertainties be more readily identified, conveyed, and acted upon?
- What are the broader implications for how we navigate complex systems?

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. The 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[1], it becomes ever more important to be aware of uncertainties and the nature of the system being faced.

In today's highly interconnected sociotechnical systems, many complexities 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. These can hinder abilities to anticipate complex system behaviours, which is fundamental to managing systemic risks and emerging issues.

Situational uncertainties often include avoidable knowledge gaps, where decision-makers miss knowledge held by other actors in the system. Surfacing and acting on these **'unknown knowns'** offers an early win and a cost-effective approach to anticipating and preparing for systemic risks (which, by their nature, can escalate and become massively expensive when dealt with reactively).

This report is a first step in raising awareness of the challenges of boundaries in complex systems and potential responses.

"The Admiral's Map"—published 1513 (Martin Waldseemüller: "Tabula Terre Nove")
The Barry Lawrence Ruderman Map Collection, Stanford
https://exhibits.stanford.edu/ruderman/catalog/xs013vp4386

1 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.

Our key point is that failure to recognise or acknowledge situational uncertainties beyond boundaries can lead to catastrophic decisions. 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. In what is often a rapidly changing environment, this task calls for on-going vigilance ('chronic unease'). In doing that, making better use of knowledge that already exists but is not shared – the unknown knowns – offers an early win in achieving safer complex systems. Complex systems do not respect boundaries – they cannot be tackled in silos.

1. Introduction

Taking decisions invariably involves uncertainty. Incomplete information and imperfect knowledge about context and system relationships is a fact of life.

Well established methods designed to help decision-makers cope with uncertainty exist. Used wisely, they can contribute to better decisions. However, they rely on the ability to identify (or imagine) the uncertainties involved. Failing to acknowledge or address uncertainties can lead to catastrophe.

Perceived boundaries affect the degree to which key players recognise, share, and understand uncertainties. In the shift from a complicated system to a complex one, this can become even more challenging. As Annex A details, complex and complicated systems are fundamentally different:

- **Complicated systems** are relatively simple, with clear boundaries and stable cause-and-effect relationships between their actors (the people, organisations, technologies, or subsystems that form the key elements of the system).

  Uncertainties can be confidently modelled, and problems solved, using well established analytical tools that are supported by research and professional judgement. There is a general expectation that uncertainties can be managed, and that the system can be controlled.

- **Complex systems**, by contrast, are largely unpredictable due to high levels of interconnectivity and associated information flows that determine how the system behaves. In addition, the existence of many different but each equally legitimate viewpoints can create substantial ambiguity (a significant feature of complexity). These factors result in dynamic interplays between the actors within the system, and between the actors and the contextual environment that lies beyond the system's boundaries (in effect, there are porous boundaries). Outcomes emerge 'bottom-up' from these interactions and can drive step changes in behaviour. The system may also cross 'tipping points', beyond which any significant changes cannot be easily reversed.

  If complex systems are to be rendered safe, their inherent unpredictability and ambiguity have to be explicitly recognised. Uncertainties need to be 'navigated' by anticipating and adapting to (potentially rapid) changing contexts. Mental models and expectations, correspondingly, need to accept flexibility and shifts towards 'coping' and 'resilience' (as opposed to 'controlling').

In practice, the split between complicated and complex systems is not absolute. Systems can change over time and transition between the two types as contexts change, or as new uncertainties, data, or knowledge emerge.

Approach taken

This report explores how perceived boundaries influence the recognition of uncertainties and sharing of knowledge. Making better use of knowledge that already exists but is not shared – the unknown knowns – could offer an early win in mitigating or navigating some of the system uncertainties.

Figure 1 sets out the report's structure. This shows how a variety of case studies are used to identify the issues and to explore potential responses. The report then concludes by framing these responses within the wider context of navigating uncertainty in complex systems. Annex B provides a glossary.

The review draws on a wide range of organisational, disciplinary, and geographical perspectives: the diversity of inputs is central to the report's approach. It builds on a combination of practical experience, literature review, interviews with relevant experts and peer review.

The review is indebted to the many people who have so generously given their time and insights. The authors thank everyone involved for their energy and thoughtful contributions (Annex C).

2. Key findings of this report

- The illusion of knowledge is dangerous. In complex systems, those knowledge gaps that are not being seen (or imagined) – the unrecognised uncertainties – can prove to be even more important than those that are. In many cases (but not all) these are what we term 'situational uncertainties', which relate to what lies beyond perceived boundaries (whether at whole-of-system or functional levels), influenced by subjective perspectives and individual motivations.
- Our review of many case studies concluded that systemic failures due to these situational uncertainties can be broadly characterised into three typologies, namely:

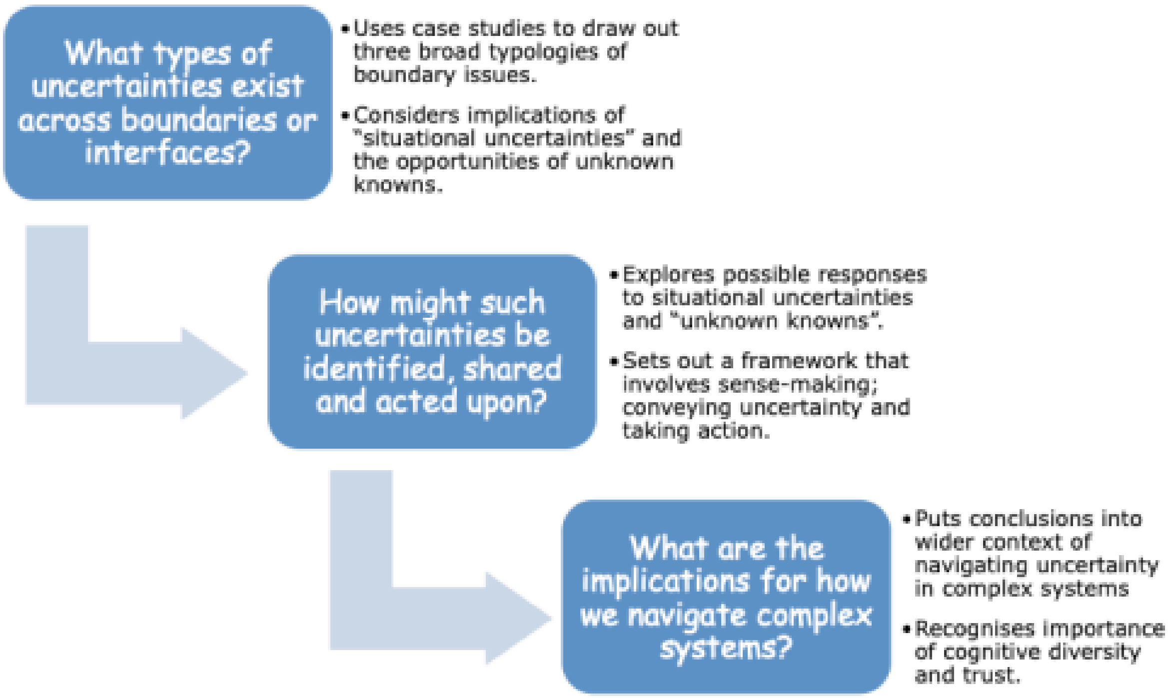

Figure 1: Structure of the report

- **Myopic:** arising from the influence of the system's contextual environment, for example, impacts from natural or social systems, or from other domains or geographies.
- **Accidental:** arising from fundamental changes to the original system over time, such as new and often intangible interconnections that modify system boundaries and behaviours.
- **Disjointed:** arising from disconnects and breakdowns in information flows across functional boundaries within the system, often influenced by physical, cognitive, or social factors.

- In many cases decision-makers do not know (or fail to act on) information held by other people or groups. Surfacing these **"unknown knowns"** would enhance safety by ensuring this knowledge becomes recognised, acknowledged, and thus able to be acted upon by decision-makers.
- Overcoming the limits of knowledge and navigating uncertainty requires a collective ability to focus on a whole-of-system perspective and share diverse insights through a cycle that involves:
  - **Sense-making:** involving a wide range of specialist and nonexpert voices, together with evolving technologies such as machine learning, in the search for information that can spot unanticipated changes to the system and its contextual environment, or that can identify and assess the implications of any uncertainties. Imagination is crucial.
  - **Conveying uncertainties:** ensuring effective dialogue and communications of uncertainties to explore divergent values, beliefs, and concerns of different people; to test the real-world limits of the designed system; and to understand where existing methods may no longer work and the issues (or signals of issues) that may emerge.
  - **Taking action:** ultimately, no action can be taken until people are willing and able to let go of existing practices and preconceptions. That relies on shared understanding of the strengths and limitations of different practices or options and, more fundamentally, on trust.
  - **Repeating the process**, on an on-going and iterative basis, each time tracking changes to the system, its dynamics, and its contextual environment to ensure its continuing integrity.
- **Navigating uncertainty** in disruptive worlds calls for mental models, approaches and leadership styles [5] that reflect the need to anticipate and adapt, crucially underpinned by trust. There is a need to raise awareness of issues that may be faced, and 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 backgrounds).

3. Complex systems: characterising boundary failures

Complex systems are porous (open) systems, with behaviours shaped by both the interactions between the actors within the system, and between the actors and the contextual environment beyond the system's *perceived* boundaries. We emphasise perceived because the concept of 'inside' and 'outside' such a system is never simple or uncontested. 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.

While, in principle, system boundaries should be defined by their purpose (or the problem to be solved), this is not straightforward. 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 [6]. 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.

Characterising boundary failures

In this section, based on our case studies, we distinguish three types of complex system failure. In each case, perceived boundaries and the resultant uncertainties they produced, led to different behaviours. Brief, illustrative examples are used to describe: the **'myopic system'**, **'accidental system'** and **'disjointed system'** (**Figure 2**).

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 use of case studies introduces the powerful lens of hindsight [7]. The perfect outcome knowledge that hindsight offers can distort the realities of the time and result in misleading pictures being presented. In this report, although each individual example relies on the investigations and findings of others, our conclusions focus more on the patterns of system boundary issues seen across these multiple examples, with the breadth of inputs mitigating hindsight risks.

The myopic system

Near sighted (myopic) perspectives can take many forms. The following examples illustrate issues that can

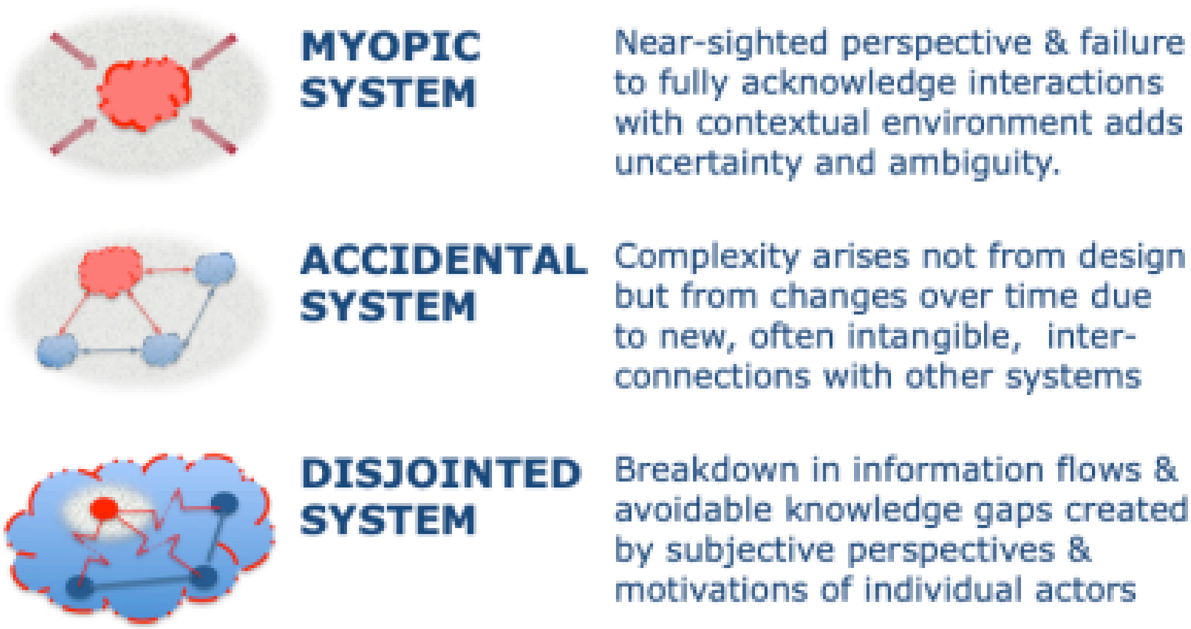

Figure 2: Typologies of boundary failures in complex systems

arise when geopolitical, social, natural contexts are not sufficiently taken into account.

- **Geopolitical influences:** In Iran, over 600 dams have been built since the Islamic Revolution in 1979. The stated benefits include managing water for agriculture, industrial and domestic uses, 'green' power from hydroelectricity, and modernised infrastructure that supports economic development. However, these dams have also been associated with widespread ecological damage, significant costs on displaced local communities and mismanagement of water supplies that has led to 'water bankruptcy' [8].

  Contextual environment: The dams form part of much broader geopolitical and social justice systems. The downstream impacts of Iranian dams affect the flow of water across geographic borders. Water shortages have prompted deadly protests in the Khuzestan province [9] where, coupled with frustrations about social inequities and underdevelopment, Khuzestanis question why 'their' water must be transferred to other regions while they suffer from thirst. Across national borders, Iran's dams affect Iraq as changes to downstream water flows in the Tigris and its tributaries damage an economic lifeline in an arid region. This is compounded by major new Turkish dams impacting the Tigris–Euphrates basin. The associated geopolitics raise the spectre of 'water wars'.

  There are direct parallels with the contentious issues created by many other major dams [10]: Egypt, Sudan, and Ethiopia all depend on inflow from the Blue Nile and have long exchanged political blows over the upstream Great Ethiopian Renaissance Dam; similarly South East Asian states are affected by China's management of the Mekong River.

- **Cultural influences:** The Bhopal disaster in 1984 led to an official death toll exceeding 5,000, with more than half a million people poisoned, as toxic gas leaked from a pesticide production plant owned by Union Carbide and spread through surrounding areas. This massive disaster resulted from the combination and accumulation of many factors, including several unheeded warnings.

  Contextual environment: Failures to appreciate the cultural differences contributed to the tragedy. Bhopal was operated by an Indian subsidiary of an American multinational (Union Carbide) and agrochemical industries in India and America operated with vastly different understandings of risk, regulation, and responsibility [11]. On-site storage of an extremely dangerous chemical, and associated emergency responses, which might be acceptable in lightly populated West Virginia failed to account for a dense urban region in India. Workforces were different: Factors that led to cheap local labour in Bhopal also forced qualified individuals out of the area to find work – leaving a limited pool of labour with a low skill set. None of these factors appear to have been adequately acknowledged.

  After the disaster, competing interests between those involved were exacerbated by further cultural disconnects. These played out in the conflicts between key actors, their differing communication objectives, and media reactions, which shaped wider responses to the tragedy. The victims did not think their voices were heard, nor did they believe that the Indian Government was able to represent their interests [12]. Long drawn-out judicial processes exacerbated the impact on victims and highlighted the power asymmetries at play. While technology moved West to East with little hindrance and insufficient regard to local conditions, transferring legal accountability the other way proved essentially impossible [13].

- **Natural-hazard triggered technological (Natech [14]) accidents:** The Fukushima Daiichi nuclear power plant meltdown was triggered by the cataclysmic Great East Japan Earthquake and Tsunami of 2011. Post-accident analyses indicate that the radiation from the accident has not led to any direct impact on human health, although the health and well-being of over 150,000 people evacuated from surrounding areas was affected to varying degrees (including early deaths) [15].

  Contextual environment: The accident resulted from poor design assumptions, faulty decision-making, and complacency, which led to insufficient awareness of the obvious dangers of siting hazardous facilities on a tsunami-prone coast. Ultimately, it was described as an organisational failure caused by "collusion between the government, the regulators and TEPCO [the operator], and the lack of governance by said parties" [16].

  While Natech accidents are often claimed as "act of god" or "black swan" events, which can be helpful in the context of insurance claims or polluter-pays defences, all too often they result from inadequate assessment or preparation for the challenging natural environments to which a plant may be exposed [17]. The investigation by the National Diet of Japan concluded that this nuclear accident was "a profoundly manmade disaster – that could and should have been foreseen and prevented. And its effects could have been mitigated by a more effective human response" [16].

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 a system.

- **Interdependencies between infrastructures** – such as electricity, transport, communications, and water supply. A power outage triggered by a lightning strike in August 2019 affected over 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. This vividly illustrates critical interdependencies.

  Changes over time: In the last decade, the UK's generation mix has moved to include a greater amount of electricity generation from many smaller generators connected to the distribution network. The total loss from these generators may have exceeded the loss from the two major power stations that shut down during the event [18]. Reviews of the incident highlight potential mismatches between the operational practices, software, and design codes developed for largely centralised electricity generation and those needed by an increasingly distributed network [18]. Added complexity is brought by the transition itself and the need to blend fundamentally different innovative technologies with legacy systems and processes.

- **Shared dependencies:** a maritime trial by the General Lighthouse Authorities of UK and Ireland, working with the UK Ministry of Defence, tested what happens when Global Positioning System (GPS) fails at sea [19]. It highlighted wide ranging impacts. Crews were overwhelmed by simultaneous alarms as GPS dependent systems failed. There was confusion on shore as the vessel's Automatic Identification System (AIS) sent information with erroneous positions and high velocities, which conflicted with radar information.

  More generally, a ship's navigation, situational awareness, chart stabilisation and emergency communications can all rely on GPS. If these are lost, continued navigational safety then relies on the crew's abilities to recognise that GPS service has failed and to operate effectively using alternative techniques (such as traditional navigational skills, that may themselves have been eroded through lack of use).

  Changes over time: 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 has created points of potential systemic instability. Examples include Chicago's O'Hare International Airport, London's Heathrow Airport, and the Suez Canal. A single shock can cause severe widespread impact by affecting these important system nodes. The plume of very fine volcanic ash created when Iceland's Eyjafjallajökull volcano erupted in 2010 caused several of the largest global airports to shut down, resulting in the greatest disruption in global air traffic since the second World War [20].

  Changes over time: the development and increasing importance of these critical nodes over time is closely linked with the evolution of the just-in-time supply chains that make use of them. The dependence on air transport resulted in an estimated $5 billion in direct losses from Iceland's volcanic eruption. These included: losses to the European tourism businesses of between £5 million and £6 million per day; Kenya's economy losing £2.8 billion because of flights to Europe being cancelled, with its farmers reportedly having to dump stocks of fresh food and flowers; Japanese car manufacturer Nissan halting production of several models because it was not able to import parts from Ireland. The indirect losses are likely to have been even greater.

  Comparable issues were seen when the *Ever Given* container ship became stuck in the Suez Canal in March 2021 – blocking it to all traffic for six days. This is estimated to have cost billions of dollars, affecting the global shipping industry and countless businesses that rely on delivery of supplies (from domestic transport providers to retailers, supermarkets, and manufacturers).

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 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" [21].

  Interface issues: 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 against those, was the dominant belief in the professional expertise of the bankers and wizardry in creating new ways of mitigating the risks. A desire to believe drowned out the conflicting views and the inconvenient facts.

  Again, from the British Academy's review [21]: "it is difficult to recall a greater example of wishful thinking combined with hubris" and the psychology of denial that failed to recognise "a cycle [before the crash] fuelled, in significant measure, not by virtue but by delusion".

- **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. Tragically, this moved from theory to reality in June 2017 as 72 lives were lost in the fire that engulfed the high-rise Grenfell Tower. The subsequent review of the UK's building and fire regulations [22] highlighted the complexity and related erosion of regulatory effectiveness that had developed over time.

  Interface issues: The review drew out how ignorance and indifference, coupled with lax enforcement and insufficient accountability in a fragmented industry, had come together to create a culture that undermined building and fire safety. Gaps across the regulatory system left plenty of scope for shortcuts and noncompliance. This was compounded by the voices and concerns of residents not being adequately listened to. This created a cycle in which things became progressively worse as the effectiveness of regulations and associated trust in the institutions involved became increasingly eroded.

  A review of the catastrophe, and comparable events in other sectors, highlights the systemic failure to learn from previous events. If this is to change, then: "If we all developed our capacity to deal with complexity and ambiguity, ensured fairly borne consequences, tapped diverse and distributed knowledge, and created safe spaces to explore deeply held contextual assumptions; and organisations practice chronic unease, governments tended to the psychological contract with their citizens, the media covered systemic issues and rebalanced power, and think thanks created accessible data to help citizens and the media hold government to account; and if communities and citizens disrupted the status quo – then, I believe, we would see change" [23].

- **Concealed risks:** the wrongful accusation and prosecutions of thousands of sub-postmasters in the UK (described as one of the largest miscarriages of justice in the UK) shows how concealment of information can pervert justice over two decades and ruin very many lives [24]. Sub-postmasters were prosecuted, convicted and sentenced for fraud on the basis that computer system (Horizon) data must be correct, when in fact there could be no confidence that the data was reliable [25]. It showed how humans, with a "computer never lies" mentality, can blindly accept the output of automated systems as reliable evidence.

  Interface issues: People were unaware of knowledge that was known somewhere else in the system: the Post Office knew there were serious issues about the reliability of Horizon [25]. This may have involved deliberate or subconscious concealment by individuals because of the potential liabilities. Equally, those receiving information may have actively excluded "uncomfortable knowledge" because of the threats to the organisation or their individual position within it. This is an example of how ignorance can be a positive achievement and not just a simple background failure to acquire, store, and retrieve knowledge [26]. Ultimately the implications go much wider: the trustworthiness of institutions relied on by society was seriously undermined.

  Note that concealment of risk may not be deliberate. It can, for example, be an unintended consequence of well-intended measures to transfer risk such as outsourced contracts.

These examples of **myopic**, **accidental** and **disjointed** typologies show how perceived boundaries influence the extent to which complex systems and associated uncertainties are understood, and the potential consequences of not recognising knowledge gaps. The next section draws on insights generated by these examples to present an overview of boundary issues in complex systems.

4. Complex systems: boundary issues

The cases described in the previous section are drawn from an extensive list of complex system failures, with the underlying issues broadly characterised in three typologies (although in practice sometimes all three may be present and interact within the same system).

They highlight one of the challenges faced: complex systems rarely have obvious boundaries. As Meadows [27] 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."

There are a number of generic points:

- 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 geopolitical 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 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.

- 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 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 that 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 of the L'Aquila earthquake were communicated to the public highlighted the multidimensional and dynamic nature of the uncertainties [28]. 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 complexity poses particular challenges to the engineering community.

Developments beyond boundaries that take individuals and organisations beyond the limits of their knowledge introduce 'situational uncertainties'. This concept is developed in the next chapter.

5. Situational uncertainty

We defined the term **situational uncertainty** to reflect the imperfect, unknown or unimagined information that lies beyond a boundary, and that therefore often remains unrecognised. This makes it distinct from those recognised uncertainties (the 'known unknowns') within, or closely linked to, a system, which can be surfaced and subsequently managed through typical risk management processes. The previously defined typologies highlight different sources of situational uncertainty.

Unknown knowns

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, as the examples in the previous section illustrated, all too often these are actually **unknown knowns**. In many system failures, performance progressively degrades until exposed by some atypical action that triggers a chain of events, which rapidly lead to failure. Despite some people or groups seeing the signals of imminent issues, or holding information that could avert or mitigate a major failure, this is not seen or not acted upon by decision-makers.

Part of the issue, according to Taleb's work on "black swans" [6] 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. All too often success is measured in terms of managing the known knowns and known unknowns, at the expense of unknown knowns.

The 'streetlight effect' [29] (**Figure 3**) is a metaphor for the tendency to seek answers where the process of seeking is easy, rather than where the answer may actually lie.

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.

Sources of situational uncertainty

The previously described typologies, summarised in **Table 1,** highlight potential sources of uncertainty. The table includes questions that might be asked by decision-makers, or those providing assurance, to raise awareness of these potential uncertainties.

In the next section, we discuss approaches that may help in unearthing such knowledge and generating value from different perspectives in ways that could offer useful and novel insights.

6. Tackling situational uncertainty

This section considers three interrelated elements of working with communities to surface unknown knowns, as part of tackling situational uncertainties (**Figure 4**):

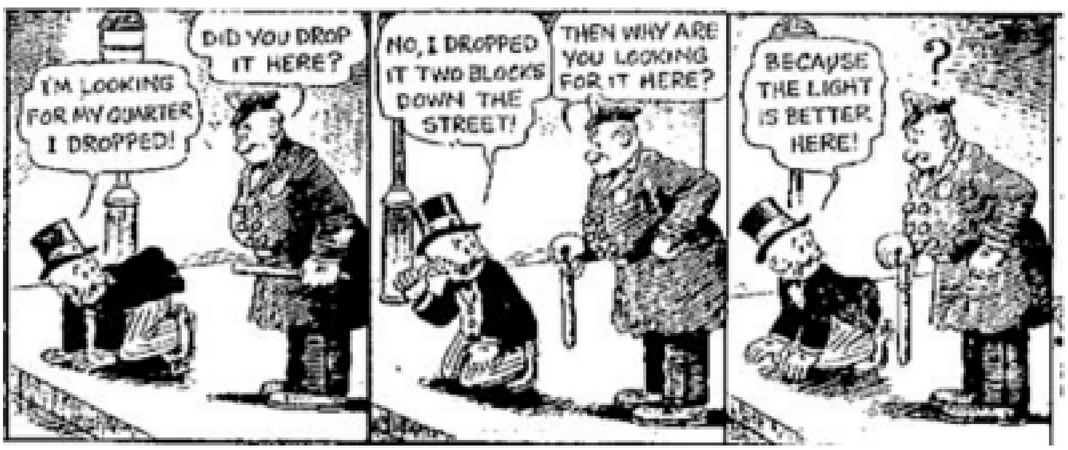

Figure 3: The Streetlight Effect [29]

SYSTEM BOUNDARIES: SOURCES OF SITUATIONAL UNCERTAINTIES		
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 (geopolitical) 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: sources of situational uncertainties

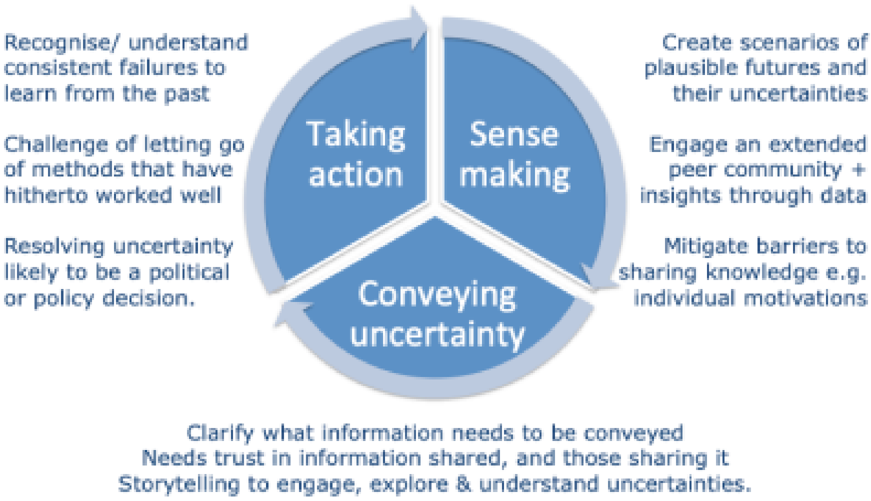

Figure 4: An approach to tackling situational uncertainty

- **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.

And then, importantly:

- **Repeat:** This cycle cannot be a one-off linear process, due to the inherent uncertainty of complex systems. It needs to be iterative and on-going to reflect the dynamics and changing nature of a complex system. The need for chronic unease cannot be stressed highly enough – there is no space for complacency in safer complex systems.

Note that the outlined approaches are more of an exploratory art than a predictive science. They need to be context specific. In practice, the resourcing demands will 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.

Sense-making

Sense-making is literally the act of making sense of an environment, achieved by organising data and information until the system and its contextual environment are sufficiently well understood to enable reasonable decisions to be taken.

Weick [30] summarises the most important aspects of sense-making as follows: "If accuracy is nice but not necessary in sense-making, then what is necessary? The answer is something that preserves plausibility and coherence, something that is reasonable and memorable, something that embodies past experience and expectations, something which resonates with other people, something that can be constructed retrospectively but also can be used prospectively, something that captures both feeling and thought, something that allows for embellishment to fit current oddities, something that is fun to contrast. In short, what is necessary in sense-making is a good story."

As human beings, we relate to stories. In coping with the varying perceptions, interpretations, and conflicting interests that are often present in complex systems, sense-making can usefully involve:

- developing scenarios as a way of capturing and synthesising plausible futures and uncertainties
- engaging an extended peer community, to benefit from diverse experience, expertise and insight
- mitigating barriers to sharing insights, such as individual motivations or uncomfortable knowledge.

At a meta-level, the **development of scenarios** [31] provides one way of identifying uncertainties and understanding the futures that *may* happen. By focusing attention on plausible futures and uncertainties, with new perspectives and options, scenarios are well suited to the ambiguities and deep uncertainties of complex systems. They can expose assumptions that might otherwise remain implicit, counter excessive self-confidence, and contribute to shared and systemic sense-making.

Most importantly, scenarios allow decision-makers to rehearse the future, consider what their responses might be in the face of a set of diverse plausible challenging futures, and, in so doing, can create 'memories of the future' that can enable quick adaptation in times of crisis.

Scenario planning can draw on insights (spanning both facts and values) from a variety of sources, including:

- the views and experiences of different actors in the system, and the diverse lenses they bring. This community might include cross-disciplinary specialists as well as nonexpert voices
- periodic reviews and assessments, or incidents in comparable systems (including in other sectors or geographies), and the questions that these may raise
- unanticipated changes within the system or its contextual environment, whether from social, natural or technological events. This relies on the ability to recognise failure in complex systems
- advanced technologies, such as machine learning or other forms of artificial intelligence, which can identify possible abnormalities in system behaviours or to model possible futures
- research, which may not only itself reduce uncertainty, but may also introduce extra knowledge that can open up wider questions.

The process of creating scenarios requires both imaginative big picture thinking at the whole-of-system level (to get an overall sense of possible behaviour), and detailed insights to understand specific risks and relationships. It is therefore critical to involve multiple perspectives, with divergent worldviews, usually far beyond the immediate organisation or system. This can be done directly at the scenario building stage, or indirectly, using interviews and research.

The scenario planning process enables policymakers to compare and contrast different potential responses for each scenario, thereby rehearsing the future. It also draws on multiple stakeholders to contribute their perspectives. This can build social capital and trust through creating opportunity for fair process [32] (even if the outcomes are not perceived as fair by all). However, this is resource intensive. The willingness to invest time and energies in doing this may require a collective consciousness of the risks involved and/or a recent incident prompting a reaction.

Another way involves what Funtowicz and Ravetz describe as an **extended peer community** [33]: other scientists and experts who add competence and can represent interests from beyond the 'official expertise' (in other words, outsiders), together with individuals personally affected by, or benefiting from, decisions but who may not have the 'usual' professional or academic background. This community can add value through their different, potentially contradictory, views, and through the insights they provide into the reality of how things are actually done (as opposed to how things are imagined to be done).

Involving a minimum level of cognitive diversity becomes especially important when dealing with complex systems where the accepted version of the world excludes knowledge that is crucial for making sense of and addressing the problem, particularly when working across different cultures (whether national, disciplinary, or organisational).

In practice, bringing together individuals from very different backgrounds, types of organisations and disciplines (spanning formal, natural, and social sciences, arts and humanities) is not easy. It can suffer from disciplinary silos, different languages, and, at worst, intellectual arrogance getting in the way of collaborative work on complex systemic issues.

Actors may also actively exclude 'uncomfortable knowledge' (including taboos or other undiscussables) that is in tension with their version of the world or their values – a well-known psychological phenomenon termed "avoidance of cognitive dissonance" [34].

Getting value from these diverse inputs thus also needs the creation of decision frameworks and shared language to support effective dialogue and debate (deliberative mechanisms). In turn, that benefits from a broader development of skills, and inclusive behaviours, to capture and synthesise the rich insights that a diverse community might bring. It also requires mind-sets willing to give sufficient emphasis to formulating and articulating the question, before rushing to answering it.

Involving an extended peer community has implications for how and when decisions are taken, and power is shared. For example, the Bhopal tragedy led to a call for wider sharing of information about hazardous technologies, including systematic risk information and detail of the hazards faced by local communities. Jasanoff pointed out that sharing such information would only be meaningful if the community had also been able to act preventively: "those with a right to know have to be given an opportunity to participate in technology transfer decisions before it is too late to choose a technology that is well adapted to the technical and cultural circumstances of the importing country" [35].

There may be specific challenges in a 'disjointed system', where barriers to sharing information may be created by the subjective perspectives and motivations of the actors in the system (whether individuals, organisations, or institutions). Here, unknown knowns may be concealed (deliberately or subconsciously) through tactics such as denial, dismissal, diversion, or displacement (potentially to avoid responsibility, embarrassment, or liability).

In such circumstances, considerable effort will be necessary to join up disjointed thinking – which relies on there being the collective will to do so. The outcomes may call for **clumsy solutions** [26] or **satisficing** – a term coined by Nobel prize-winning psychologist Herbert Simon, which involves searching through the available alternatives until an acceptability threshold is met: "decision-makers can satisfice either by finding optimum solutions for a simplified world, or by finding satisfactory solutions for a more realistic world. Neither approach, in general, dominates the other, and both have continued to co-exist in the world of management science." [36]

What is clear is that sense-making will become increasingly important in the future. As our world becomes more complex and ambiguous, we are likely to collectively encounter a growing number of intractable problems. Significant knowledge gaps (uncertainties) will expand and failure to recognise these can create a false sense of security. Yet, all too often, there is no collective will to engage and share thinking, with insufficient attention to creating the space and resources for sense-making.

While we may feel that we cannot afford to do this in a resource limited project, in a complex system we might not be able to afford not to do so. As the 'streetlight effect' metaphor highlighted (previous section), there is a nearly irresistible attraction to put effort into managing the known knowns and known unknowns, where success can be measured, at the expense of surfacing the unknown knowns. It is essential, but also exceptionally challenging, that we switch effort from tackling those things that are easily measured to those harder but much less well-defined issues.

Conveying uncertainty

The challenge of conveying uncertainty, and especially hitherto unrecognised uncertainty, is that too much can overwhelm, while too little can oversimplify. But unless relevant insights are shared effectively, with the appropriate level of detail, key actors in the system are likely to put too much or too little faith in the underlying science or evidence.

That calls for:

- clarity in the nature of information that actually needs to be conveyed
- sufficient levels of trust in both the information shared, and those sharing it
- use of methods such as storytelling to better engage, explore, and understand uncertainties

In practice, **the information that needs to be conveyed depends on the decisions that people face** and needs to be considered accordingly. The social context is also critical: no process is likely to achieve its aims without a clear understanding of the social and political connotations of a particular situation, and the uncertainties involved and their implications (risk).

One of the dilemmas is how to express uncertainties without undermining scientific and institutional credibility or triggering unintended responses when many uncertainties may be at play. In L'Aquila, for example, the local community was allegedly given fatal reassurances by scientists a few days ahead of the 2009 earthquake that killed 309 people [37]. A tragic loss of life might have been mitigated by communicating not only the facts but also the possibilities: a public reminder of emergency procedures and active engagement instead of a high-profile down-play of the earthquake warning [28].

To state the obvious, communities are diverse, with varied cultures, values and beliefs that influence their risk perception (and hence appreciation of the implication of uncertainties and associated dangers). Renn (elaborating the Post-normal Science theory of Funtowicz and Ravetz [33]) highlights how the communications approach required will vary accordingly, to find a common language through which communication can proceed and develop. Responses can range from the presentation of factual evidence for the most straightforward issues through to the worldview debates (and wicked problems) that encompass personal identification with a set of social values and choices.

Renn describes three typical communication levels, determined by intensity of conflicting views about the issue at stake and its degree of complexity, as shown in **Figure 5** [38]:

- The first level, grounded in the knowledge and expertise of technical experts, is where the focus may be on factual arguments about probabilities, exposure to hazards and the extent of potential damage, and also ensuring that these are understood by the intended audience.
- The second, more intense, level is more based on the institutional experience and competence to manage risks (as opposed to assessing them). The focus is more on the distribution of risks and benefits, and the trustworthiness of institutions to manage risks in a way that matches public expectations. In a complex and multifaceted society that can become difficult.
- At the third level, conflicting and competing perspectives that reflect different social values or world-views shape appetites for risk. In this case, neither technical expertise nor institutional competence and openness are adequate conditions for risk communication. Instead, it needs a fundamental consensus on the underlying issues. This implies that the communication requirements of the first and second levels (risk information or two-way dialogue) are insufficient to find a solution that is acceptable to all or most parties, so options such as citizens panels or mediation processes might be involved. This takes us back to clumsy solutions (satisficing) described above, and the critical need for there to be a collective will to address the issues.

An obvious point is that it is **difficult to convey uncertainties well if there are low levels of trust**. This may be because information is incomplete or

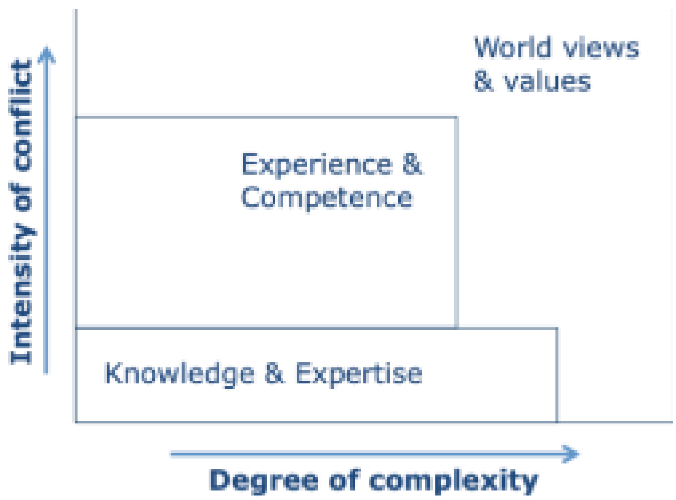

Figure 5: Three levels of concern in risk debates (Renn, 1998 [38])

of poor quality; or be due to organisational incompetence (which can itself result from ineffectiveness in grappling uncertainty); or arise because of perceived expert bias (which may be, in part, a feature of experts and the public perceiving risk differently) [39]. A constructive way of mitigating such issues is to use independent peer review and transparency to dissociate vested interests from any outcomes.

Issues of trust become even more problematic if those uncertainties conflict with what the receiver of this information believes to be ethically right. This was seen in the previously described case studies: the legal proceedings after Bhopal; the possible exclusion of uncomfortable truths (deliberately or subconsciously) by the Post Office; or across interdependent critical infrastructures, where a lack of coherent communications can create significant issues for the community) [40]. Such disconnects can also become a focus for controversy, potential media bias, or sensationalism.

There is also a strong tendency for decision-makers or experts to reframe higher level conflicts at lower levels of complexity, allowing focus on those issues where the expert is fluent [38]. As Kaplan puts it: "It comes as no particular surprise to discover that a scientist formulates problems in a way which requires for their solution just those techniques in which he himself is especially skilled." [41]

Stakeholders are thus forced to use first level (factual) arguments to rationalise their value concerns, which can often be misunderstood by the expert and labelled as 'irrational'. Frustrated, the public may then retreat to direct action and protests. The end result is a cycle of escalating public distrust and disillusionment – not least because once a belief becomes established it is almost impervious to counter arguments.

One of the options for dealing with this is through **story telling**. This is an inherent human way of exploring both meanings and possibilities. Eidinow describes how it allows for the inclusion and exploration of multiple perspectives and a variety of different outcomes [42]. Because stories engage with the complex cultural structures that shape perception and understanding, they offer a potentially powerful tool for sense-making. They can be very effective for exploring and understanding uncertainties and thinking through their potential implications.

As Eidinow notes, research on story telling suggests that using stories to present data can be a more effective way of communicating an idea than using numbers, because it allows data to be understood in terms of lived experience. This goes beyond empathy: this is part of our inherent cognitive processing by which we make sense of the world around us. In turn, our environments are shaped by the stories that we tell.

These narrative features can be deliberately developed in structured strategy exercises, such as scenario planning (which create a set of stories of the future). This can allow for the collaborative development of stories that provide a shared basis for decision-making across multiple communities [43]. Stories about possible futures may not only describe possibilities, they can also lead to actions (or indeed, inactions) that realise those possibilities [44]. As with scenario development, specific skills are needed. In this case, the ability to consider all the relevant factors and develop meaningful storylines around them, to highlight how the uncertainties might unfold effectively.

Many qualitative scenarios are subsequently quantified. 'Quantitative story telling' (QST) provides an example of this [45]. It offers a cyclical, iterative process that balances both 'semantic' phases (work with stakeholders to understand how issues are framed) and 'formal' phases (work to quantify these issues using data and analytical tools to characterise uncertainties). QST incorporates data and expertise arising from different disciplinary perspectives (for example, social and natural sciences) as well as from stakeholders themselves. Applications of QST, to date, have focused on sustainability issues, for example, exploring the use of alternative water resources for irrigation in the Canary Islands. (This parallels questions that our case study drew out for Iran.)

Taking action

Gaining a shared awareness of uncertainties is necessary but insufficient to ensure safety. There is an equal need to embed the new practices, behaviours, and mental models that are more appropriate to complex systems. History shows that delivering this type of change is not straightforward:

- There are lessons from consistent failures to learn from the past.
- It is challenging, particularly in a crisis, to let go of methods that have hitherto worked well.
- Ultimately resolving uncertainty is likely to be a political or policy decision.

A recent review of **failures to learn from the past** [46] flagged an abiding need to think more systemically about managing complexity, and noted the impacts of:

- decision-making and priorities influenced by factors such as changing incentives, such as outsourcing and the adequacy of advance planning and information flows
- the often conflicting advice from different areas of expertise, some of which might be prepared for different types of contexts

- the institutional frameworks, including regulatory and political considerations.

A more generic risk comes from systematically underestimating the surprises that the past held (and holds) as we review past failures. Fischhoff demonstrated this in his seminal work on "hindsight ≠ foresight" [7], showing how the very knowledge that makes us feel we understand the past – outcome knowledge – may lead to hindsight bias and thus prevent us from learning anything from it.

People's willingness to let go of their existing preconceptions and practices was a theme explored by Weick. He used "Dropping one's tools" as a metaphor to illustrate the need for unlearning, for adaptation, for flexibility [47]. In his study, Weick considered 27 firefighters (Mann Gulch 1949 and South Canyon 1994) who lost their lives because they did not follow orders to drop heavy tools in order to outrun a wildfire.

Weick summarised 10 reasons that have been put forward to explain why it was so difficult for these firefighters to take the counter-intuitive advice to drop their tools. These range from the practical (the roar of the fire meant that people did not hear the order); through to trust (people persist when they do not trust the person who tells them to change); and identity (the fusion of tools with professional identity, so that under conditions of threat people retain their tools). All 10 reasons are credible. They show some of the many, interdependent, coherent reasons motivate people not to change.

Weick noted that these interconnected reasons only became visible through a focus on relationships. He concluded that the obvious question of "how to survive" may not dominate everyone's attention at the same moment, and it does not mean the same thing to everyone. Survival is just one of many criteria that apply when tackling an unpredictable fire. And because people persist in making complex trade-offs among multiple criteria and ambiguous cues, they may fail to realise when they are in serious trouble. While sense-making may be most needed when we feel under threat or crisis, the psychological mechanisms that get engaged to deal with fear (such as rigidity) are the ones that can hamper sense-making.

It would probably have required some 'memories of the future' for the firefighters to have understood the context in the split second that they needed to. This temporal aspect is important. Having to respond at pace in the middle of a crisis is fundamentally different to having the luxury of time to consider and explore options.

The approaches to sense-making and conveying uncertainty described earlier in this section rely on having space for reflection. They highlight the benefits of responsible anticipation and preparation. People learn about situations by asking "what if" and then exploring the possible different strategic responses. That is why working through scenarios or small, controlled, experiments can help.

Even when action has been taken, it is important to remember that systems and their contextual environments continue to change and evolve. The cycle does not end: taking action is just one part of the continuous and repeating cycle applied to tackle situational uncertainty. It calls for what high hazards industries describe as **chronic unease** (a term originally conceived by Reason [48]). That involves constant vigilance and wariness: a state of mind that is the opposite of complacency.

Ultimately, what to do in the face of situational uncertainties may be **more of a political or policy question than a scientific one**. Therefore, recognising current power dynamics is crucial, as creating the necessary conditions to deal with complexity relies on having leaders who endorse the new practices needed by complex systems, who are able to influence and persuade, and who can therefore make things happen.

7. Navigating uncertainty in complex systems

The examples in this report, together with what we see in the world around us today, highlight the growing shift of manageable complicated systems towards disruptive complex ones. This development is bringing:

- more uncertainty to a world that strives for certainty
- more complexity, as issues cross, interact, escalate across hitherto neatly defined boundaries
- more pace in decision-making, enabled by and in response to technological advances
- more fragmentation, with issues more visible and legitimately competing views
- more chaos, especially as contradictions of old and new ways play out in transition
- a shifting emphasis from managing to coping, introducing societal complications.

Many complexities are likely to arise at system boundaries, yet complex systems have no respect of such boundaries. Our review has shown how perceived boundaries can obscure emerging issues, risks, and knowledge gaps. It highlighted how the 'situational uncertainties' that lie beyond boundaries can compromise safety and function.

Situational uncertainties can be triggered by different mechanisms. We identified three typologies (myopic, accidental, and disjointed) to characterise the different behaviours and distinct challenges seen. A recurring theme was the presence of avoidable knowledge gaps, the unknown knowns. Surfacing these 'situational uncertainties' and capitalising on what is already known by others (if not by us) will help: complex systems cannot be tackled in silos. The responses described (sense-making, conveying uncertainty and taking action) provide options for achieving this.

Safer complex systems: questions to explore

The broader series of case studies commissioned by the Safer Complex Systems programme could further enrich insights into 'situational uncertainties' and associated challenges. **Table 2** summarises the questions that emerged from our research and could provide focus for future exploration.

Navigating uncertainty in complex systems

The challenge we face in navigating uncertainty may lie not in the new ideas or methods, but in recognising when the old ones are no longer relevant. Pirsig's metaphorical "south Indian monkey trap" [2] highlights how knowledge that has long served us well can become obsolete and lethal [49]. In this case, that includes appreciating that complex systems are quite different to complicated ones. Without that explicit recognition, 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.

That means that we must not only listen to those answers and insights that could reduce levels of uncertainty, but that we must also pay even more attention to those questions that give us pause for thought. In complex systems, knowledge gaps that are not being seen (or imagined) – unrecognised situational uncertainties – can prove to be even more important than those that are.

If we are to achieve our goal of safer complex systems then, whatever our track record, the most important part of our task may be recognising and remembering where the limits of our knowledge and analytical methods lie. In doing that, we also need to capitalise on the insights and information held by others. Complex systems cannot be tackled in silos.

8. Recommendations

Navigating the multidimensional challenges, pace, and uncertainties of disruptive worlds relies on capabilities to **anticipate and to adapt** [50]. The generic capabilities supporting adaptive leadership styles [5] (an ability to anticipate, to listen and reflect, and to adjust responses to emerging issues) also underpin methods, set out in this report, for sense-making, conveying uncertainty, and taking action.

However, even with such adaptive capabilities, 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.

Introducing new methods that improve agility and adaptation will therefore need clarity, resources, and capabilities that may not currently exist. Alongside this, new methods will be required, with strong leadership and clarity of message to ensure that everyone plays their part and makes the necessary shifts in mental models needed to ensure the safety of complex systems.

There are actions that need to be taken now if we are to prepare ourselves for systemic risks and increasingly disruptive worlds. We group our recommendations under three themes:

- **Raise awareness:** No new approaches are likely to be adopted without first developing a collective understanding of the threats and opportunities. There are two dimensions here: first recognising complex systems as fundamentally different to complicated ones (Annex A); and second recognising that what is not seen or imagined beyond perceived boundaries – the unrecognised uncertainties – can prove to be even more important than what is.

  A key message would therefore be to remain alert to the realities of a fast-moving, highly interconnected system because solving one problem could surface other unexpected issues. Therefore, even when facing immediate issues in one element of the system, there is value in carving out the time, space, resources, and situational awareness needed to keep sight of the system as a whole and its emerging dynamics and patterns of behaviour.

  This calls for education and communications materials that can build wider awareness through practical examples. Not all issues will be complex, therefore it is crucial to establish indicators that allow decisionmakers to differentiate between the many straightforward issues where established methods can work well, and those disruptive ones with radically different demands.
- **Prepare for disruptive conditions:** In times of crisis, there is a tendency to reinforce existing maps and mental models, increase our reliance

2 The old south Indian monkey trap is described by Pirsig as a hollowed-out coconut, chained to a stake, with rice inside which can be grabbed through a small hole. The monkey's hand fits through the hole, but his clenched fist cannot fit back out. He is suddenly trapped, not by anything physical, but by an idea; he is unable to see that the knowledge that had long served him well – "when you see rice, hold on tight!" – is not only obsolete but lethal.

	Challenges	Questions to explore
1.	**Framing the realities of complex systems**	
	Approaches to safety are often based on the premise that you can measure, plan, predict, control, and manage. In complex systems, which are largely unpredictable and ambiguous, this approach is not achievable. Complex systems require fundamentally different mental models and ways of communication, which acknowledge uncertainty and its implications—by the experts as well as society at large.	• *What do we collectively understand as constituting a safer complex system?* • *How do we frame and bound our issues at the right level?* • *How can we embrace uncertainty? How do we listen not only to those answers that reduce uncertainty, but also and even more so to those questions that give pause for thought?*
2.	**Enabling trustworthy big picture perspectives**	
	Many of the biggest issues and risks that society faces span geographic, institutional, and societal boundaries. They have complex externalities that affect different stakeholders in very different ways: those ultimately bearing the risks and consequences of failure can be very distant (in space or time) from those taking the risks and gaining rewards. Choices and trade-offs are deeply value-laden and influenced by political contexts, which leads to competing world-views and conflicting values: finding common ground becomes increasingly difficult in fragmented societies.	• *Who is best placed to articulate trade-offs between precaution, innovation, and resilience?* • *What is the optimal balance between deep domain knowledge and system flexibility? How is that achieved?* • *How can we bridge existing institutional boundaries, and also draw in an "extended peer community"?*
3.	**Surfacing uncomfortable knowledge**	
	Yesterday's safer complex systems will almost certainly not be those of tomorrow. Understanding the limits of our knowledge (our ignorance), and how assumptions may become invalidated over time, is critical to having safer complex systems. Surfacing 'uncomfortable knowledge' is a specific challenge. Recognition or sharing of such knowledge is actively excluded (subconsciously or deliberately) because of expert bias or threats to the organisation, individuals within it, or other taboos. Ultimately that undermines the trustworthiness of institutions relied on by society. Conversely, done well, such knowledge sharing can enhance safety.	• *Where are the current limits to our knowledge and analytical systems?* • *What is responsible for ensuring that knowledge limits are reviewed – governance frameworks? Whistleblowing?* • *How do we create the conditions and build the trust that enables uncomfortable knowledge to be surfaced and shared?* `

Table 2: Questions to explore

on old information, and focus increasingly on the detail rather than the overview. These tendencies inhibit action. We need to prepare for disruption while we still have the intellectual and temporal resources to do so. When sense-making is most needed, these resources will be unavailable.

Approaches such as scenarios and storytelling offer options for developing our 'memories of the future' and increasing our understanding of where limits to knowledge are being approached. Importantly, these can explicitly acknowledge (and convey) the uncertainties and inherent ambiguities to be faced, as well as the trade-offs involved in balancing many different, legitimate, views. This can help with building confidence and trust, and also enable policymakers to stress test strategic choices without risking the costs of potential failure.

Disruptive conditions call for a variety of new skills to support inclusive deliberations, the imagination to explore plausible futures, and fast-review, learning, and re-design capabilities to adapt to changing times.

- **Invest in relationships and deliberative mechanisms:** This allows a dispersed and diverse community to, respectfully, share and debate ideas, insights, and different perspectives, and to build collective understanding and social trust. In doing this, advantage can be taken of virtual communities and communication channels such as social media. These provide new ways of co-creating a shared agenda, communicating compelling narratives to a broader audience, and acting as a source of information.

Complex systems are dynamic, interconnected, and potentially disruptive. If we are to address the types of complex issues being faced and uncertainties involved, this will require input from a diverse range of sources. It is likely to bring together individuals from very different types of organisations and a wide mix of disciplines (spanning formal, natural, and social sciences). This breadth of perspectives can be further enhanced (and trust built) by engaging interested individuals from outside established institutions, who may not have what is seen as the 'usual' professional or academic background. Complex systems do not respect boundaries and they cannot be tackled in silos. The challenge of overcoming the disciplinary silos and different languages that can get in the way of collaborative work by diverse and distributed communities on complex systemic issues will therefore need to be addressed head-on.

This will require substantial investment in 'decision science' capabilities [51]. With many of the frequently used methods relying on expert judgement, safeguards are also needed to mitigate pitfalls such as cognitive bias (which may manifest in, for example, being dismissive of non-experts, or being unwilling to listen to those challenging the status quo).

These recommended actions are 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.

Annex A: Complicated or complex?

Complex not complicated

A prerequisite for a safer complex system is the ability to distinguish between those complicated issues and systems where current practices and risk-based methods have continued relevance, and those complex, disruptive ones that may require a radically different approach:

- The US government review on the response to the catastrophic New Orleans floods noted that: "Officials at all levels seemed to be waiting for the disaster that fit their plans, rather than planning and building scalable capacities to meet whatever Mother Nature threw at them … One-size-fits-all plans proved impervious to clear warnings of extraordinary peril. Category 5 needs elicited a Category 1 response." [52]
- The collapse of large-scale ocean fisheries has been partly attributed to the use of simplified scientific models. These models do not reflect the complexity of ocean ecosystems, yet there is little acknowledgement of the implications of this partial knowledge and insufficient recognition of the possible impacts of the resulting uncertainties. The governance frameworks, industry incentives, and precautionary responses that are derived from these models then compound the problem, by assuming that they are dealing with certainty. The outcomes can be catastrophic [53].
- The collision of what are viewed as independent risks can add to the challenge. Issues that may ordinarily be viewed as complicated can become complex. Ferocious wildfires in California or hurricanes in the US Gulf region regularly lead to evacuating and temporarily sheltering thousands of people, often using high density transport and accommodation. Now consider doing this in a pandemic, while maintaining the social distancing required to avoid COVID-19 escalating. [54]

Overview of the differences

The complexity of a system is relative and the difference matters. The mental models and approaches required are different. In general:

- **Complicated systems** are considered to be well bounded, with stable cause-and-effect relationships between actors, and uncertainties that can be confidently modelled using well established analytical tools, supported by research and professional judgement.

  Having stable system relationships, which can be reliably observed and measured, enables the outcomes from interventions at different scales to be confidently predicted. A problem can be broken into its constituent parts, analysed at an elemental level and the outputs then reassembled to produce an overall picture. This reductionist approach works well for many problems, as seen by the wealth of knowledge gained through such methods being applied in scientific research. Comparable approaches also underpin many governance and regulatory models.
- **Complex systems**, by contrast, are largely unpredictable due to high levels of interconnectivity and associated information flows that play a significant role in determining how the system behaves. In addition, a legitimate and irreducible

plurality of viewpoints can result in significant ambiguity (a significant feature of complexity). These factors combine to create a dynamic interplay between the actors within the system, and with the contextual environment that lies beyond their perceived boundaries (the system has porous boundaries).

Outcomes emerge 'bottom-up' from these interactions, and can lead to 'phase transition' or transformative changes. For example, a local failure in one system can rapidly cascade to the others and cross 'tipping points' after which any significant changes cannot be easily reversed. This 'emergence' process means that reductionist approaches do not work.

The unpredictability and ambiguity inherent in complex systems creates conditions that have the frequent capacity to surprise. However, this does not mean that system behaviours are always a product of pure chance. Systems often have the property of self-organisation – they can structure themselves, create new structure, learn, diversify, and add complexity. Even complex forms of self-organisation may arise from relatively simple organising rules – or they may not. [27].

In many instances, the patterns of interactions between the components of a complex system can provide structure. Some of these can be stable and long lived, such as the rules that allow birds to flock in intricate coordinated ways; or they can be ephemeral and subject to constant change, as is the case with most social norms. Although systemic behaviours cannot be predicted on the basis of these patterns, broad directions of change can often be anticipated by viewing the system as a whole. That creates scope for identifying feedback loops, possible leverage points, and potential sources of system surprises. These will go a long way to early sighting of emerging issues, experimentation, and adaptive responses, which support effective governance.

Table 3 provides an overview of how a complicated system differs from a complicated one [55]. The initial framework report for the Safer Complex Systems programme [56] provides further details, with generic descriptions, characteristics and examples of a complex system.

Responding to complexity

The conceptual framework set out in **Figure 6** provides a way of visualising and communicating these differences. It can be used to acknowledge both the level of uncertainty faced and the sophistication of the responses that may be needed.

Complicated Systems	Complex Systems
Complicated systems are closed, their boundaries relatively fixed, impermeable, and easy to determine.	Complex systems are open, making it difficult or impossible to determine their boundaries.
Complicated systems are ordered and deterministic. They can be fully understood in terms of the properties of their component parts, and they always tend towards equilibrium.	Overall behaviour of complex systems is not determined by the properties of their elements but their interactions. The system is usually far from equilibrium but without dissolving into random disorder; it exists 'at the edge of order and chaos'.
Cause-and-effect relationships are linear such that for each input to the system there is a proportionate output. We can identify a clear cause for each observed effect and predict system-level outcomes of each change.	The relationship between cause and effect is nonlinear and effects are usually the result of several interacting causes. Because of feedback loops, we cannot establish clear cause-and-effect relationships or predict system-level outcomes.
Complicated systems can only evolve with the help of an external force. System elements are static and not able to adapt to changing conditions on their own. If a key part of the system breaks down, the whole system will stop functioning, unable to repair itself.	Elements in a complex system are able to learn and adapt to changing conditions. Simultaneously adapting elements give rise to self-organisation. As a result, complex systems can display remarkable resilience and sometimes even continue functioning if key system elements break down – or can cross a tipping point and rapidly flip into an alternate state.
Because cause-and-effect relationships in complicated systems are stable over time, any kind of change is reversible.	In complex systems, change creates path dependencies that may be difficult to alter. If we could turn back time to the same starting conditions, the system is unlikely to evolve in exactly the same way.

Table 3: Complicated or Complex? Key differences (Based on [55])

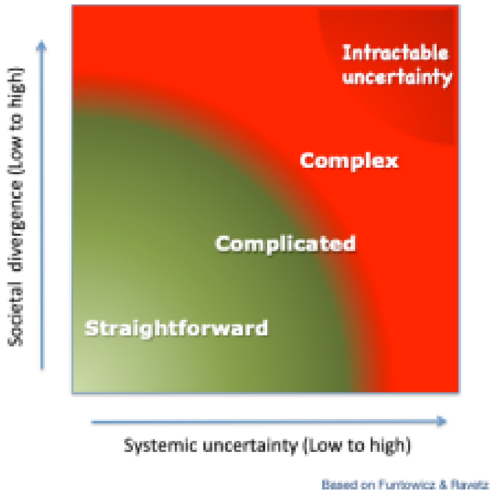

Figure 6: A spectrum of complexity (based on Funtowicz and Ravetz, 2020 [33])

This diagram was originally used to illustrate the changing regulatory responses needed as complexity increases [57]. An overview of the diagram is provided below, with further detail in [57]. It draws on the distinctive decision-making framework set out in 'post-normal science', which considers interactions between societal and technical elements. This framework is designed to tackle issues that are changing rapidly and in unpredictable ways, a process that makes them even harder to control and attracts conflicting societal views on how best to address them.

The model (Figure 6) considers the system in terms of its predictability (systemic uncertainty) and societal perspectives (societal divergence):

- **Systemic uncertainty** relates to the predictability of behaviours within the system. It reflects the extent of the technological or scientific uncertainties across the system, as well as those linked to the human, social, and organisational interactions. The complexity can be further amplified by pace (of change and of decision-making), by scale (crossing sector boundaries), by nature (continuous fluidity and volatility), or by long timeframes.
- **Societal divergence** is one element of the contextual environment beyond the system boundaries. It focuses on values, taking account of the contested views and dynamic political contexts with dilemmas for example on long-term or legacy issues. The intensity of this scale, as society diverges and becomes less cohesive, is influenced by aspects such as trust, ethics, and social order. These divergences can be amplified by what is at stake (the criticality of the decision). At the highest levels, there are hotly contested issues that may drive significant activism, present contradictory world-views, or highlight conflicting international ethical perspectives.

The levels of complexity shown in **Figure 6** reflect the different types of responses that might be necessary or possible. There are no neat boundaries between these categories, but in general:

- **Straightforward** issues can be addressed using standard analytical routines and procedures.
- **Complicated** issues may have greater knowledge gaps or variable conditions identified, but these uncertainties can be dealt with through professional judgements supported by research and scientific experimentation. Well established risk-based analytical procedures remain relevant.

  In engineering contexts these range from long-established risk-based analyses such as FTAs (fault tree analyses), FMEAs (failure mode and effects analyses), and HAZOPS (hazard and operations analysis), to newer methods such as STPA (System-Theoretic Process Analysis [57]), and FRAM (Functional Resonance Analysis Methods [59]).
- **Complex** issues require expectations to shift towards 'coping' as opposed to 'controlling'. Responses will tend to be more focused on understanding relationships and patterns of behaviour, to anticipate, and then adapt to the uncertainties. This is different to the conventional expectation of 'solving' the problem, and hence 'managing' the system. The systemic risks associated with complex systems are over-extending conventional risk management practices and create new unsolved challenges for policymaking in risk assessment and risk governance [4]. It means acknowledging that decisions have to be made under uncertainty, thereby placing even more emphasis on recognising and acknowledging the uncertainties involved; being aware of the assumptions and limitations of the analyses, data, or solutions applied; and keeping alert to signals of emerging issues.

A particular issue is that modelling and simulation tools applied in engineering contexts are typically intended for predictable, if complicated, systems (some are outlined above). These may become dangerously inappropriate when applied to complex systems. Innovative use of technology, such as 'digital twins', aim to inform real-world decision-making through highly realistic simulated worlds that combine assumed and actual, real-time, data. While offering considerable potential for highly complicated and, potentially, complex systems there is still significant investment required to realise their promise [60].

- **Intractable** issues may prove to be almost unmanageable in practice. For engineers and technologists, whose innovations may be applied in completely unexpected ways, the risks of inadvertently creating such issues is not insignificant. Tim Berners-Lee's reflections on 30 years of the internet make the point: "while the web has created opportunity, given marginalised groups a voice, and made our daily lives easier, it has also created opportunity for scammers, given a voice to those who spread hatred, and made all kinds of crime easier to commit [61]." Concerns about Artificial Intelligence have prompted a call for action from scientists concerned about comparable issues [62].

  Intractable issues may surface, for example, where there are extreme levels of uncertainty; where unstable social dynamics are built on top of a technical underpinning; or where extensive new interconnections cross previously distinct boundaries at extreme pace. Awareness of the limits of current knowledge becomes increasingly important, and monitoring of relevant leading indicators of associated risks allows progress with caution. [63]

Annex B: Glossary

A system is an interconnected set of elements coherently organised to achieve a purpose. It will have essential properties, linked to its purpose. Any of its constituent elements, interconnections or purposes can change over time, with a system's history influencing how it behaves today. The past does not, however, predict the future.

The actors are the interconnected elements of the system. These can be people (including those affected by, or benefiting from, the system), organisations, technologies, or subsystems. Many of the interconnections in systems operate through a flow of information, with this flow itself having a significant role in determining how the relationships operate.

The contextual environment lies 'outside' the system [63]. It includes factors that can create turbulence and change, but that are beyond the direct control of actors in the system. These factors can not only influence, but also be reflexively affected by, the system behaviours.

The boundary defines what is 'inside' or 'outside' the system. While it bounds the actors, it is not a barrier: two-way interactions between the actors and the contextual environment influence how the system behaves and evolves. In a complex system the boundary is porous, and the definition of boundary is linked to the system's purpose. The boundary can change over time.

Complex systems refers to those systems where high levels of interconnectivity and complex relationships between the actors, together with interactions with the contextual environment, make the system's behaviour largely unpredictable. Generic descriptions and characteristics of a complex system are provided in the initial framework report for the Safer Complex Systems programme [55]. Differences between complex and complicated systems are provided in Annex A.

Uncertainty refers to limited knowledge, where imperfect or unknown information makes it not possible to exactly describe the existing state or to predict future outcome(s) of the system. The existence and nature of uncertainties can be seen or imagined – and from this plausible events derived. It commonly includes epistemic uncertainty (gaps in knowledge) and aleatoric uncertainty (variability in parameters). 'Situational uncertainty' has been added here to characterise the uncertainties beyond perceived boundaries (**Figure 7**).

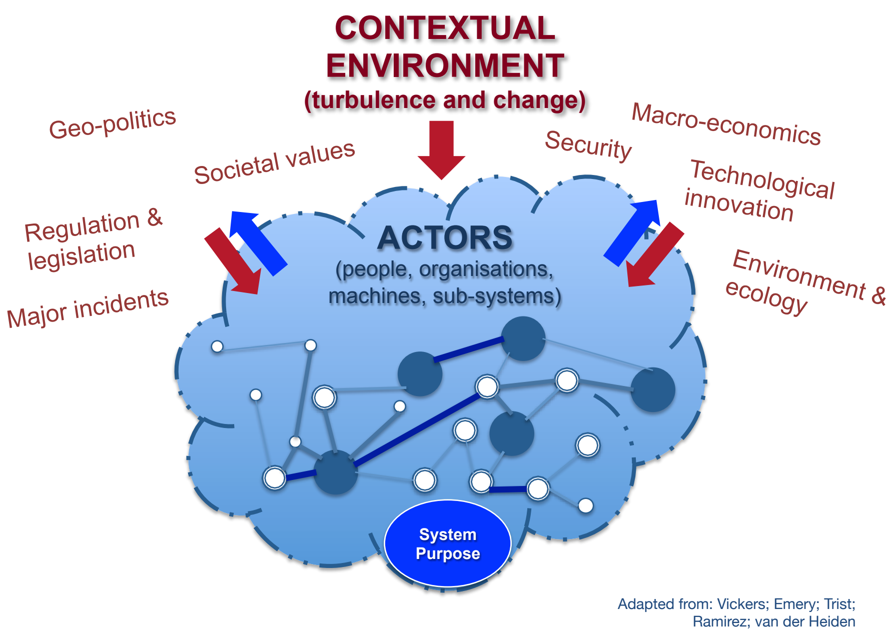

Figure 7: Schematic of system (Adapted from [64])

Annex C: Contributors

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