EngineeringX

Safer Complex Systems Case Studies

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The Engineering X Safer Complex Systems mission seeks to enhance the safety of complex systems globally.

The views and opinions expressed in the case studies are those of the authors and do not necessarily reflect the views of Engineering X.

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Chapter 1: Introduction

The Safer Complex Systems mission

All around the world people rely on critical infrastructures to survive, stay safe, and maintain a good quality of life. Much of this infrastructure is made up of complex systems that are highly interconnected, interdependent on one another, and constantly evolving. The list of complex systems is long, continually growing, and increasingly sociotechnical, including: supply chains providing fresh food from around the world to local supermarkets; power systems extracting energy from wind, sunshine, tides, biomass, and fossil fuels, and making it available 24/7 in sockets around our homes; healthcare systems linking frontline staff with pharmaceutical research, PPE providers, professional training, and accreditation; international data networks connecting phones, computers, search engines, and media; and, the financial system allowing international credit card usage and providing finance for business and industry.

We live in an increasingly complex and unpredictable world

Some complex systems are engineered – that is, there is a plan, the participants are known in advance and there are protocols and regulations in place. A city metro system may be complex, but there is little ambiguity over its geographical extent, assets, operations, or responsibility for the safety of the network. Other complex systems can occur ad hoc – there is no central authority, players join and leave at will, and regulation may be covered by multiple jurisdictions. COVID-19 demonstrated that the PPE supply chain is an ad hoc system. From time to time, people find themselves in a complex system-of-systems that, until it failed, no one had thought of as connected. Failure of the electricity supply has demonstrated how interconnected many of the essential services in a community have become.

Failures of complex systems can have catastrophic consequences for people's lives

The rapidly-changing nature of the world we live in means that these complex systems exist in the presence of swiftly emerging technologies and unprecedented global risks and at ever greater levels of uncertainty and unpredictability. When one complex critical infrastructure system fails, many other complex systems are also affected, which can have catastrophic consequences for people's lives. To address this problem, in 2019, Engineering X launched a £5 million five-year mission to enhance the safety of complex infrastructure systems globally.

Our strategy

The Safer Complex Systems mission is guided by our strategy, which seeks to account for and adapt to the lessons we learn as we go. Our programme of activities is guided by three phases, as shown in **Figure 1**, and is focused on building capabilities in four themes, as shown in **Figure 2**.

Advocating is important because we believe stronger communication between engineers exposed to risk and senior leaders accountable for management will improve safety in complex systems and help to save lives. Convening is important because different cultures internationally approach safety and risk management in very different ways, and we can all learn from each other. Education is important because, as our world becomes increasingly complex, things get more difficult to predict as we can no longer base our approach to risk management on things that have happened in the past. Governance is important because it creates the environment in which a complex system is designed, built and operated. It can be a catalyst for contributing towards, rather than helping to prevent, systemic failure.

Collectively, we believe that progress in these four areas is critical to designing, operating, and

Figure 1: The three phases guiding the Safer Complex Systems mission

GOVERN Supporting innovative collaborations and experimental mechanisms to test new ideas for complexity-appropriate policy and regulation	**EDUCATE** Develop written case studies and innovative, educational tools to support engineering education and professional development
ADVOCATE Supporting researchers to spot emerging safety challenges and supporting professional engineers to spot systemic risk and advocate within their organisations and beyond for measures that mitigate against it	**CONVENE** Build and convene an active, diverse community of complex systems experts and build mechanisms to facilitate knowledge sharing across sectors and disciplines globally and the application of academic knowledge into practice to enact change

Figure 2: The four themes through which Safer Complex Systems aims to build capabilities

managing safer complex systems. We are mindful of the importance of harnessing diverse perspectives by seeking input from people from different parts of the world, from different professions, disciplines, and sectors, and with different life experiences.

Our journey

To date, we have focused on the Learn and Build phases. Throughout numerous workshops, events, and engagements with our community members from all around the world, we have gathered insights and evidence to inform our activities and produce reports.

Our 2019 and 2020 Workshops highlighted the need for a lexicon of safety, formulation of acceptable levels of risk and foundations underlying the key themes in our current strategy and brought together hundreds of experts from over 20 countries to inform the scope of a global review on the safety of complex systems.

Safer Complex Systems: An Initial Framework, also referred to as *The York Report*, establishes the current state of knowledge and offers a new framework for understanding and improving the safety of complex, interconnected systems in a rapidly changing and uncertain world. This framework, shown in **Figure 3**, describes how risk moves through a specification/design phase and an operations phase, during which periods mitigation is possible, and manifests as systemic failures during operation. Interventions to reduce the risk are enabled or constrained by three layers – governance, management, and task/technical layers.

Our study exploring the *Exploring the safety of super-sized structures*, highlighted the fact that few large structures exist simply as engineering structures, as they are often thought of, but rather most form part of complex sociotechnical systems. Convoluted feedback loops and interdependencies between natural systems, human-made systems, individuals, and organisations give rise to emergent and adaptive behaviour, which makes examining, and understanding complex systems particularly challenging.

The Safer Complex Systems case studies

The Safer Complex Systems community identified a lack of case studies, which may provide a useful tool for education and professional development, as evidenced by their use in MBAs and business, on complex systems. To address this gap, in 2020, we held a call for proposals of case studies on complex systems under two categories:

- Type A: Case studies covering well-documented events where the authors do not need to undertake significant research.
- Type B: Case studies into events that have not been fully documented and the authors need to undertake more extensive research, before writing the case study.

Each proposal was reviewed by two experts in the specific field and all proposals were reviewed by our case study steering committee. We proceeded to commission the development of 18 unique case studies (10 of Type A, 8 of Type B) by awardees from across academia and industry. The case study development was a dynamic process in itself, conducted over a period of 18 months by the awardees, in collaboration with their own networks and under the mentorship of experts from our case study steering committee, chaired by Professor Brian Collins CB FREng.

As you will see in the following pages (see Chapter 2: Case studies), the case studies cover a wide variety of complex systems successes and failures, past and present, around the world – from train derailments in the UK, to flood protection in the Netherlands, systemic failures in nursing home care in Australia, emergence of cycling systems in

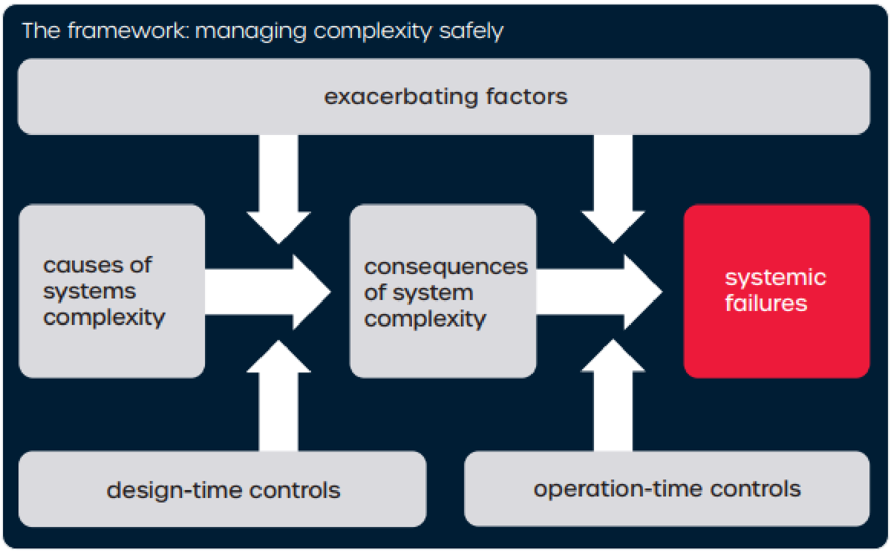

Figure 3: The York Framework for examining complex systems

Colombia, fire risk management in Bangladesh, South Africa, and the US and failure of humanitarian supply chains during COVID-19. By examining specific events, and reflecting on the *York Framework* (**Figure 3**) where relevant, these case studies seek to provide insights into how the design, construction, operation, management, and governance of complex systems may result in safe or unsafe outcomes. With a cross-sector, multidisciplinary and global lens, it is possible to draw out common key lessons learned from across the collection (see Chapter 3: Conclusion), and we encourage readers to explore all case studies, rather than only those of direct relevance to their sector, so as to maximise transfer of knowledge.

Safer complex systems terminology

There is a substantial body of theory and practice in the study of complex systems and, whatever we include or exclude here, will no doubt cause pleasure and pain in equal measure to different readers. Given the challenging topic area, we like to think that any thoughtful work – these case studies included – to better understand complex systems should be appreciated as an opportunity to reflect and learn, both as an author and a reader, rather than be intended or siloed as a 'right' or 'wrong' effort. For those readers less familiar with the study of complex systems, we have provided definition of several key concepts in terms that we find useful, below.

What is a system?

A system may be thought of as a set of elements in dynamic interaction such that they exhibit properties which cannot be found in any of the standalone parts. That is, a system is greater than the sum of its parts, with properties that are emergent. For example, a tyre is an element of a car system with the emergent property of transport. Systems may be classified into domains. For instance, the Stacey Matrix in **Figure 4** classifies systems as simple, complicated, complex, or chaotic, with respect to increasing levels of uncertainty and disagreement in decision-making.

What is the difference between complicated and complex?

Complicated and complex are often mistakenly used interchangeably, as noted in **Figure 5**. Complex is defined as something constructed of various

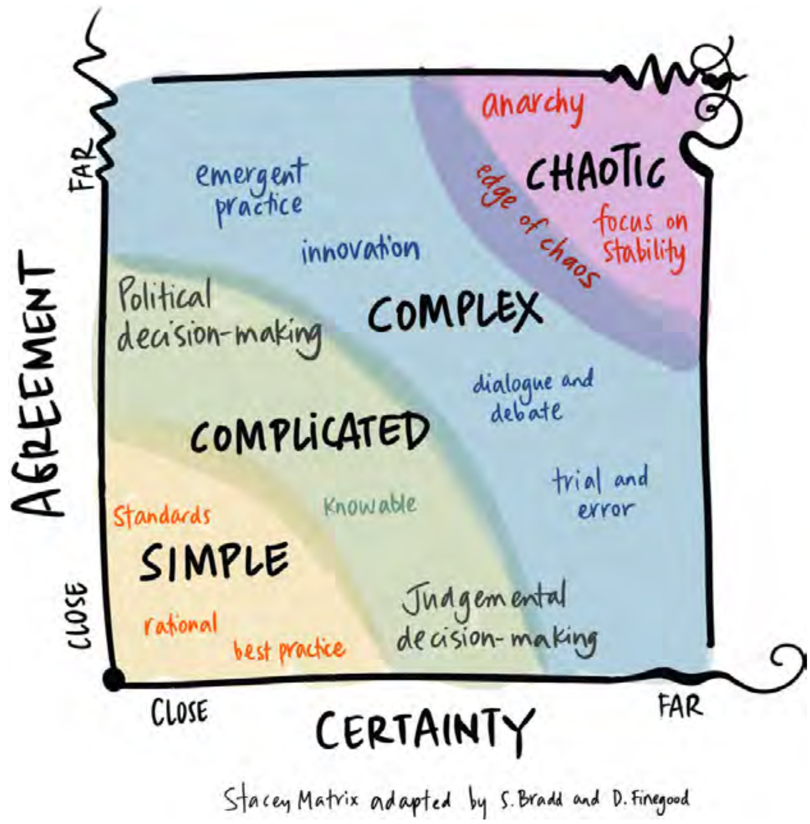

Figure 4: The Stacey Matrix classification of systems with respect to decision-making[1]

coordinate bond [c17 from Latin *complexus*, from *complectī* to entwine, from *com-* together + *plectere* to braid] > 'complexly *adv* > 'complexness *n*

USAGE *Complex* is sometimes wrongly used where *complicated* is meant. *Complex* is properly used to say only that something consists of several parts. It should not be used to say that, because something consists of many parts, it is difficult to understand or analyse

Figure 5: The definition of complex (Source: Collins English Dictionary)

interconnected components. Complicated refers to a high level of difficulty. Complexity does not evoke difficulty, and something that is complicated may not necessarily have many interconnected components.

A complex system is one including several independent systems not structurally linked to each other but interacting. There may be complex systems that are simple to understand and complicated projects that are not complex. For an example of the latter, the design and build of the Eurostar cross-channel trains, involving 16 different partners in three national consortia with dozens of subcontractors, was complicated but not complex. The project could be described by the traditional project management tools – including work breakdown structure, responsibility matrix, Gantt chart, interface schedule – and the requirements were well-defined. By contrast, the international banking system in 2008 was highly complex. The numbers of 'players' was unknown and was continually changing, they were subject to many different regulatory regimes and each had a different set of objectives, frequently in direct conflict with those of others.

What is the difference between systemic vs systematic?

Similarly, in common usage, systemic, and systematic are often used interchangeably. However, systematic describes the way a process is done, while systemic is used to describe the fundamental nature of a system. Cleaning a house can be done systematically – working through room-by-room and completing a schedule of tasks in each. By contrast, racism and sexism are systemic in that it is fostered and perpetuated by a given system of power, while a systemic infection is one that affects the whole body. These case studies take a systematic approach to examining systemic features of complex systems.

What do we mean by safer complex systems?

Safety is the condition of being protected from, or unlikely to cause, harm or danger. Safety itself can be considered as an emergent property of a system. This is because, while we can design into a system appropriate measures and mitigations of discernible or knowable risk, safety, or the lack of it, emerges from the dynamic interactions of all the parts, not all of which can be known.

As an emergent property, there will be numerous known and unknown ways to increase – or, for that matter, decrease – safety in any given complex system at any given moment in time, such as by implementing mitigating and adaptive interventions against known risks and generally building resilience and reducing vulnerabilities in the system to unknown risks.

Beyond informing future activities under our Safer Complex Systems mission, we hope that the cross-cutting lessons learned (see Chapter 3: Conclusion) brought to light by these case studies will help to create safer complex systems globally.

References

1. Drawing Change (2022). Stacey Matrix adapted by S. Bradd and D. Finegood. Available at: https://drawingchange.com/project/simple-complicated-and-complex-decision-making-new-visual/

Chapter 2:
Case studies

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Cyber-physical system shortfalls in the 2011 Brisbane flood

By Dr Giuliano Punzo

Executive summary: While fuelled by unprecedented rain, the most catastrophic effects of the 2011 Brisbane flood can be traced back to system-level shortfalls. This case study analyses the dynamics that led the Wivenhoe dam's operations to aggravate rather than alleviate the flood. Responsibilities can be mapped to three levels, and it is shown that decision making suffered from multiple pressures that had built up for more than 20 years. Ultimately, this case study shows the importance of decision-making integration across soft and hard infrastructure in cyber-physical systems, and the consequences of failing to do so.

Tags: Wivenhoe dam, Millennium drought, water infrastructure, water security, river catchment, urban planning, damage, casualties, Australia

The inquiry into the 2011 Brisbane flood revealed the role of the Wivenhoe Dam management and operations, exposing its cyber-physical nature. Cyber-physical identifies those systems where the physical components are strongly coupled to their control, which is operated, supervised or steered by humans. The naive assumption that a dam is a large, yet conceptually simple infrastructure is challenged by considering the complex system emerging from the interaction of the dam with the surrounding natural, economic, social and political environment. This case study analyses the dynamics that led the dam's operations to aggravate rather than alleviate the flood. This will be related to the multiple pressures acting on the dam and its management. Looking beyond the flood event, it is shown how failing the dam's objective of mitigating the flood had its roots in a decade of decision making that ended by cornering the dam's operators and forcing them to choose between a bad and a potentially disastrous outcome. The case study highlights the importance of the integration of decision making across soft and hard infrastructure in cyber-physical systems. This can be generalised to engineering systems that play a role across multiple complex systems, such as the climate, the natural and build environment and the dynamics of large organisations.

Section 1: Background and information

The events that led to the second highest flood in Brisbane in 35 years, on 13 January 2011, started much before the January torrential rains. The events that are reported here rely on the official report by the Queensland Flood Commission [1].

Built on a flood plain, the city of Brisbane (Queensland, Australia) has a long history of flood events, with records dating back to 1841. In the January 1974 flood, the reference gauge in the Brisbane business district measured a water height of 5.45m (also known as gauge height). This prompted the building of the Wivenhoe Dam and the consequent creation of Lake Wivenhoe in the Brisbane River catchment. At Ipswich, the Brisbane and Bremer rivers merge and flow toward the estuary located in the city of Brisbane. The completion of the Wivenhoe Dam was not sufficient to avoid the 1995-96 flood and, more importantly, the flood in January 2011, which caused 24 fatalities and damage in excess of $2.55BN [4].

When conceived, Wivenhoe Dam was meant to serve the double purpose of alleviating floods in the wet season as well as droughts in the dry season. In this, it would work together with the other reservoirs under the Seqwater jurisdiction, in particular with the North Pine Reservoir and the Somerset Lake, north of the Wivenhoe Lake. The operations of the Somerset and Wivenhoe dams are coordinated during floods to maximise mitigation. All three reservoirs have flood mitigation compartments, that is a capacity dedicated to alleviating floods beyond the 100% Full Supply Volume (FSV) or Full Supply Level (FSL). Consequently, it is normal for a dam, which has a flood mitigation compartment, to exceed 100% FSL during a flood event without risking its structural integrity. However, the flood compartment of the North Pine Dam is only 0.5% of the FSV and has, therefore, no flood mitigation capabilities by design. More details for the Wivenhoe and Somerset dams are offered in **Table 1**, while their location is visible in **Figure 1**.

Between 2000 and 2009, Southeast Queensland suffered the most severe drought in the region's recorded history, remembered as the Millennium Drought [5]. In October 2010, the Bureau of Meteorology (BOM) notified the Cabinet about the possible end of the droughts with an exceptional wet season ahead. A 75% chance of above median rainfall was forecast in Southeast Queensland between November 2010 and January 2011. Established La Niña patterns would have brought an active cyclone season. The levels of the Wivenhoe, Somerset and North Pine reservoirs, however, were not lowered, despite being close to FSV (**Figures A1** and **A2** in the Appendix),

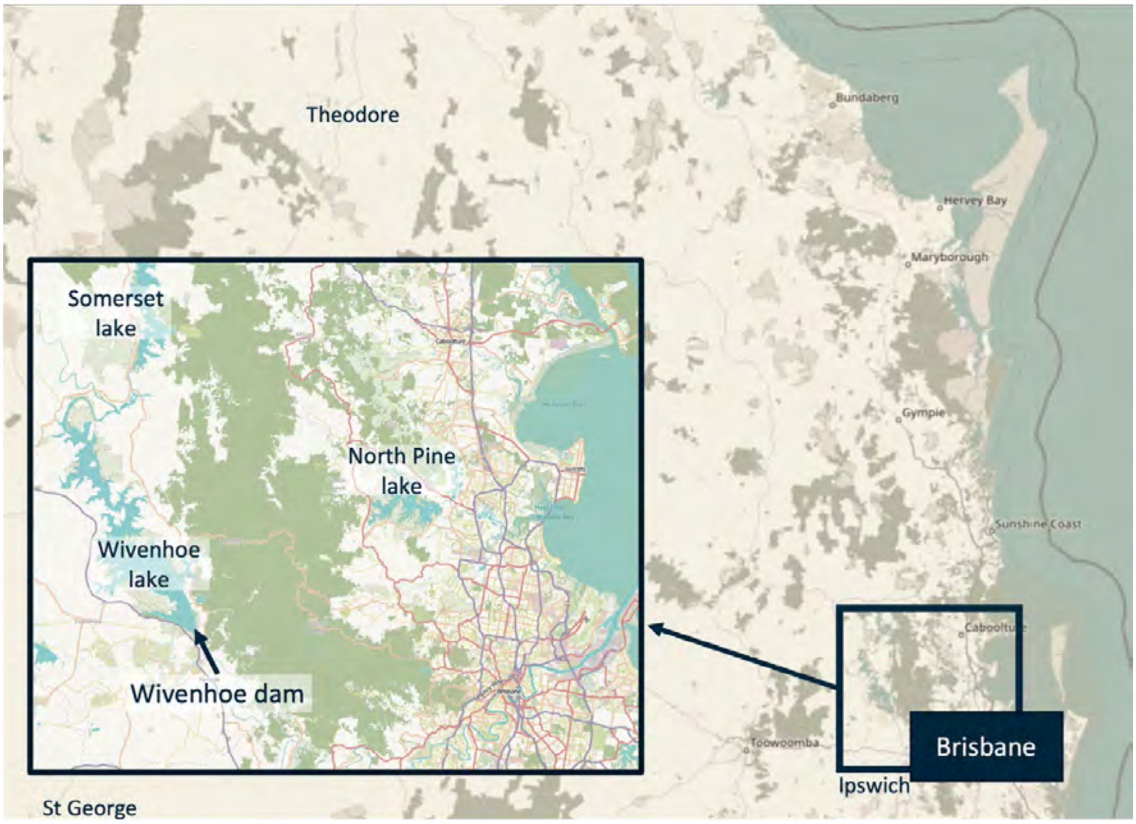

Figure 1: The city of Brisbane and the dams in the immediate vicinity providing for water security and flood mitigation (Source: Map data © OpenStreetMap HOT contributors)

Reservoirs in the immediate vicinity of Brisbane	Full supply Volume	Flood compartment	Notes
Wivenhoe	1,051,000 ML for current OFSL (EL 65.9 m AHD).	2,080,000 ML between EL 65.9 m AHD and EL 80.0 m AHD.	Controlled release through radial gates, sluice gates and fuse plugs as safety devices
Somerset	303,000 ML for current OFSL (EL 97.0 m AHD).	705,000 ML between EL 97.0 m AHD and EL 108.7 m AHD.	Controlled release through cone valves, sluice gates and crest gates. The outflow feeds into the Wivenhoe Lake
North Pine	214,302 ML full supply level, is 39.6 m AHD	the level at which gate openings are triggered, 39.65 m AHD, 1,000 ML between 39.6m and 39.65m AHD.	Not linked to Somerset and Wivenhoe.

Table 1: Characteristics of the dams in the immediate vicinity of Brisbane. The split between Water Supply and Flood compartments refer to the Operational Full Supply Level (OFSL). AHD stands for Above Australian Height Datum [2]

meaning that the only flood protection they could offer was from their flood compartments.

As the weather front approached Brisbane from the north, flood peaks occurred as early as 4-10 December in the Balonne River at St George and the Dawson River at Theodore.

By the end of December 2010, localised floods had already occurred along the Bremer and Brisbane rivers. However, the official start of the 2011 Brisbane flood main event was not until 6 January 2011. This is the date indicated in the official reports, including the Queensland Flood Commission of Inquiry report. On 12 January 2011, the 1974 flood gauge records were broken at Ipswich for the Bremer River (15,000 properties flooded) and in the business district of Brisbane, for the Brisbane River, which on 13 January experienced a major flood peak of 4.45 metres, affecting more than 14,000 properties. On the same day, the so-called strategy W4 was invoked, consisting of the full opening of the Wivenhoe radial gates, with the consequent release of water. This was triggered by the water level approaching the fuse plugs, which are safety devices meant to release water when the level puts the dam's structural integrity at risk. They are the last resort to avoid the dam collapsing. If the water had achieved the fuse plugs, the release would have happened anyway and in an uncontrollable way. Strategy W4 made this release controllable, although the volume of water released was no different as the strategy prescribes full opening anyway.

On Thursday 13 January 2011 major floods occurred throughout most of the Brisbane River catchment area, most severely in the catchments of the Lockyer Creek and Bremer River (major tributaries of the Brisbane River) where numerous record flood heights were experienced. Beyond the loss of 24 lives in the Lockyer Valley and one in Brisbane, an estimated 18,000 properties were flooded in metropolitan Brisbane, Ipswich and elsewhere in the Brisbane River Valley. A timeline of the events can be seen in **Figure 2**, where decision making milestones are also present, which are explained in the following sections.

Section 2: Analysis and insights

Four angles on the Brisbane flood

Angle 1: The joint operations of Wivenhoe and Somerset dams

On the technical side, Wivenhoe and Somerset dams are operated together to minimise the impact of floods. Starting at or close to FSL, the inflows are balanced so that both levels rise at the same rate. This is commonly known as following the target line (**Figure 3**). During the 2011 flood event, both the Somerset and the Wivenhoe dams started with empty flood compartments, but at 100% FSL. Indeed, the FSL of the Somerset Dam was 99m, one cm more than the actual level recorded on 31 December 2010. Wivenhoe Dam's FSL was set at 67.0m and the actual level was 67.69m on 31 December 2010. The fuse plugs are activated at 75.5m for the Wivenhoe Dam while the Somerset Dam cannot exceed 109.7m AHD. To avoid this, dam operators can open the gates and start the uncontrolled release to the same effect. This is triggered by a number of conditions, including but not limited to, the water level, its rising or falling trend and the precipitation forecasts. Among these, the water level at Wivenhoe should not exceed 74m AHD and, according to the manual [11], the spillway gates are not to be opened for flood control purposes prior to the reservoir level exceeding 67.25m.

At 21:00 on 11 January 2011, the Dam Safety Regulator was asked for permission to exceed a level of 74.0m in Wivenhoe Dam for a maximum of 12 hours in an extreme attempt to avoid invoking

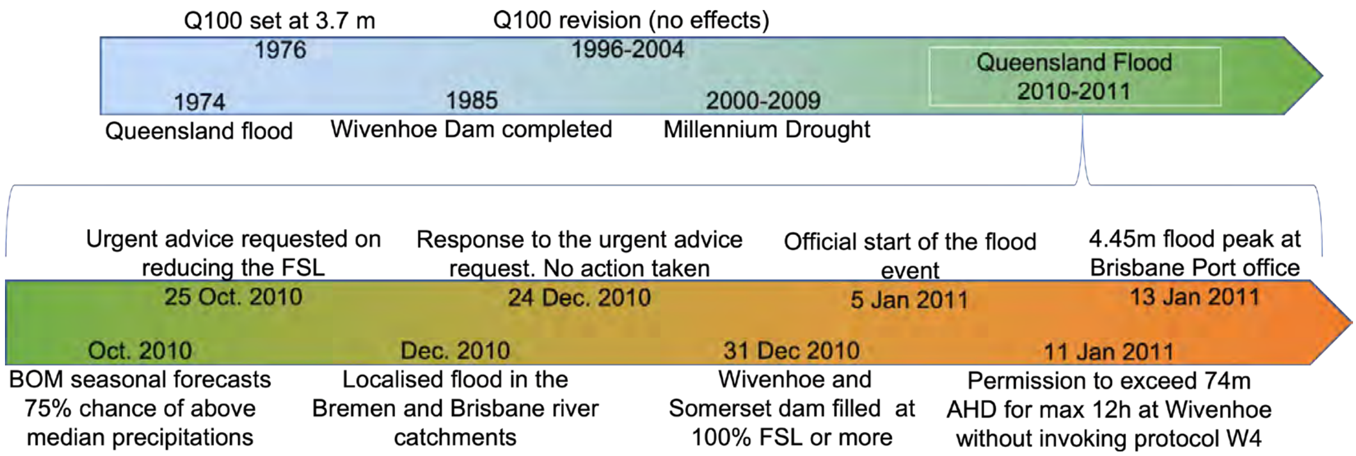

Figure 2 : Timeline of the events leading to the 13 January 2011 flood peak. Explanations about acronyms and event details can be found in the report.

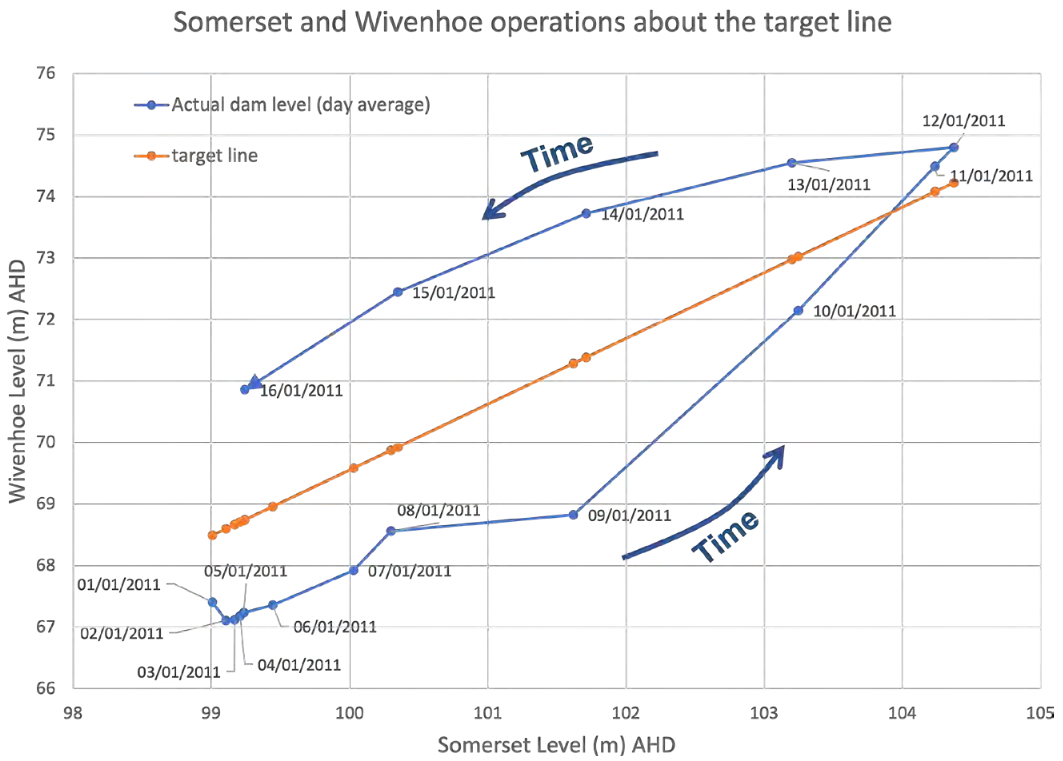

Figure 3: Target line for the levels of the Wivenhoe and Somerset dams

strategy W4 (uncontrolled release of water), provided the safety of the dam could be guaranteed. Permission was granted. The rise in the Wivenhoe Dam level was also due to the inflow from the Somerset Dam, which was already above the 102m level, meeting the conditions for which, according to the operation manual, water had to be released, flowing into the Wivenhoe Lake.

The actions taken were all in line with the Wivenhoe operation manual. This prescribes that, providing the safety of the dams is not compromised, where early opening of the gates and/or varying the operational procedures at Somerset Dam can keep the lake level below 75.5 metres, those steps should be taken to prevent fuse plug initiation. Also, the manual prescribes that the senior flood engineer may exercise reasonable discretion in moving to strategy W4 earlier if this is able to prevent the triggering of a fuse plug [11].

The flood commission inquiry concluded that, considering the flood events from 6 January onwards, dam operators took a reasonable course of action. The dam gates were operated without any impediment and both Somerset and Wivenhoe dams maintained their structural integrity. In addition to this, the Queensland Flood Commission found no evidence against the appropriate use of the operating target line [1].

Angle 2: Building and more building in a flood plain

In the past 50 years, the Brisbane population has increased at a steady rate, passing from one million in 1974 (the year of the last record-breaking flood, in the aftermath of which Wivenhoe Dam was conceived) to two million in 2011 [8]. This posed a problem which is twofold: first, the urbanisation expanded in a flood plain. This means more and more properties were built knowing about the flood risk. The second aspect to consider is the freshwater demand, which during the dry season has to be mainly satisfied through the North Pine, Somerset and Wivenhoe dams.

Given the very small flood compartment of the North Pine Dam, flood alleviation capabilities are to be sought only through the Wivenhoe and Somerset dams. Between 1974 and 2011, the flood mitigation capability leaped forward with the construction of Wivenhoe Dam. Yet, the number of properties at risk and the demand for freshwater did likewise in the 37 years separating the two events.

After the 1974 flood, the construction of the Wivenhoe Dam was seen as a definitive solution, building an 'immunity myth', hence an enabler of the urban expansion in the flood plain [12].

In fact, the increased water demand eroded the margins separating the conflicting objectives on which Wivenhoe Dam was constructed and is operated. The 2009 version of the Wivenhoe Dam manual, relevant to the 2011 flood, lists them in order [4,11]:

1. Ensuring the structural safety of the dams;

2. Providing optimum protection of urbanised areas from inundation;
3. Minimising disruption to rural life in the valleys of the Brisbane and Stanley rivers;
4. Retaining the storage at Full Supply Level (for water supply purposes) at the conclusion of the Flood Event;
5. Minimising impacts to riparian flora and fauna during the drain down phase of the flood event.

From the list above, it is immediately obvious that there is a conflict between objectives 2 and 4.

Angle 3: The Q100

The Annual Exceedance Probability (AEP) is often indicated through the so-called Q100, that is the height of water in a flood event that is likely to occur once in 100 years and is often considered as synonymous with the height of flood water that can be recorded annually with 1% probability. This is derived using models and available information and used as a basis for flood risk management worldwide and, in particular, in Australia. The Q100 is evaluated at different geographical locations and drives planning policies. At the time of the 2011 flood, the Q100 corresponded to 3.7m at the Brisbane River Port Office Gauge [5]. This value was calculated based on the level of the flood water reached during the 1974 flood, then reduced following models that considered the mitigating effects of the Somerset and Wivenhoe dams. The higher the Q100 the more limitations are imposed on urbansiation and the kind of planning possible.

Decisions on the Q100, which must be set as a policy matter by the Brisbane City Council (BCC), are hence taken under conflicting pressures from different stakeholder groups.

In 1996, a year characterised by intense precipitations and localised floods in January and May, a revision of the Q100 was commissioned. First delivered to the BCC in 1998, the best estimate of the Q100 was 5.34m at the Brisbane port office gauge. This estimate was subject to several reservations from the BCC's Water Resources manager as it was based on the conservative assumption that the Wivenhoe and Somerset dams were at 100% FSL at the start of the flooding event. Despite two subsequent analyses that confirmed best estimates all close to 5m, BCC did not approve any changes to the Q100 and eventually left it unchanged. In 2003, a special commission was asked to estimate the Q100 again, within just five weeks and without undertaking any further modelling. The new recommended figure was 3.3m, subsequently adjusted to 3.51m and finally 3.16m in 2004. The BCC was satisfied with the figures all being below the 3.7m existing one and made no change to it. Indeed, it appears that the 2003 figure was derived on the understanding that the Wivenhoe and Somerset dams could reduce downstream peak flood flow rates between about 35% and 60%, which is far from what happened in 2011. [5,10]

Looking at the 2011 event, the peak flood level at the Brisbane River Port Office Gauge was recorded at 02:57 on 13 January 2011 at 4.45m.

The time in which the crucial decisions about the Q100 were taken, as described above, partially overlapped with the Millennium Drought (2000-2009) [9], which also witnessed an uninterrupted population growth. Both factors are likely to have pushed such crucial decisions onto a political ground, even when they should have been science based only. To this effect, it is important to report verbatim the Queensland Flood Inquiry Commission's report: "A flood study is a scientific investigation; it involves no matters of policy" [1, pg 41].

Angle 4: Inertia and (lack of) leadership

Although Seqwater kept the formal management responsibilities, it subcontracted the operational management of the Wivenhoe, Somerset and North Pine dams to Sunwater during flood events for more than 10 years up until 1 July 2011. This arrangement saw many responsibilities as operator of the dams delegated during times of flood. However, it appears that Seqwater did not ensure the continuity of the arrangement throughout the 2010/2011 wet season. The actual agreement expired on 31 October 2010 and was not extended until 24 December 2010; but no formal agreement was in place between 1 November and 23 December 2010. The flood management service by Sunwater continued nonetheless, according to the terms of the expired agreement, with acceptance from Seqwater [2]. This dangerous situation may be considered as a symptom of the intricate decision-making pathways crossing several political and technical levels and the possible lack of identified leadership in the time leading to the January 2011 flood event. The crossing of communications at different levels that resulted in no actions taken about the FSL of the Wivenhoe and Somerset dams are even more striking evidence of this.

In October 2010, the Minister for Natural Resources, Mines and Energy, Stephen Robertson, launched an inquiry into the possibility that the full supply level of Somerset, Wivenhoe, North Pine and Leslie Harrison dams might temporarily be lowered. Indeed, the Bureau of Meteorology had warned the Cabinet about the forecast for an unusually intense wet season ahead, with a 75% chance of above median rainfall in South-East Queensland and of an active cyclone season. The forecasts were based on evidence of established La Niña patterns, expected to persist until at least

March. Such events are historically correlated with tropical cyclones in the Coral Sea, leading to above normal rainfall persisting over Queensland.

As a result of this, the Water Grid Manager and the Minister agreed on a formal letter in which the minister asked the Water Grid Manager's urgent advice about options for, and benefits of, releasing water from 'key storages' – at a minimum, Wivenhoe, North Pine and Leslie Harrison dams – in anticipation of major inflows over the coming summer. This correspondence was dated 25 October 2010. Although anticipated through informal briefings, an official response to the letter was dated 24 December 2010. In essence, the response suggested that the benefits of a temporary reduction in the level of Wivenhoe and Somerset dams (to 95% of the combined full supply level) would have been negligible as protection against medium and major flood events. To improve flood mitigation, the release should have been as great as 16% or more. However, it should be noted that on 24 December, Queensland had already suffered increased precipitations and localised floods and on 25 December, Category 1 Cyclone Tasha crossed the coast. The minister eventually decided that no actions should be taken.

On 20 January 2011, when the scale of the devastation was apparent, the minister requested that Seqwater's report on the recent flood events at Wivenhoe and Somerset dams include considerations on the effect of the full supply levels. After maintaining the 'no action' line and noting that the tension to ensure water security motivated the FSL decision on policy grounds, on 13 February 2011 Mr Robertson had to reconsider his decision. He issued a media statement in which he announced that Seqwater had formally recommended that Wivenhoe Dam should be temporarily reduced to 75% of its full supply level as a precaution against the 'second strongest La Niña pattern in history'. The impact of this decision is visible in the volume reduction shown on the right side of **Figure A1** in the appendix.

The inertia that emerges at this level of control over the dam operations saturated the ability of the engineering level of control and is striking evidence of the cyber-physical nature of the system.

A complex system framework for safety

The Wivenhoe-Brisbane case can be illustrated through the Complex System Safety framework [6] which provides a conceptual arrangement of the elements in a complex system that lead to its systemic failure. Such elements are the exacerbating factors; the causes of complexity; the consequences of complexity; the design-time controls; and the operation-time controls. In the Wivenhoe-Brisbane case, the failure is not the physical collapse of the dam but can be found in the system-wide issue of failing to conciliate the needs of a growing population with long term management strategies of the whole cyber-physical system, including the urbanisation as well as the green and blue infrastructures and the people. This eventually led to the uncontrolled release of water from the dam, which is the physical and visual aspect of the systemic failure.

Based on the description of the events and the analysis of the different dynamics, the opacity of the decision-making process is the common trait to all the exacerbating factors, which became explosive when projected in highly expected and highly uncertain La Niña patterns.

The Wivenhoe system presents complexities on all levels. Technical complexities are linked to the fact that the reservoir is part of the network of reservoirs meant to provide relief from both floods and droughts. Moreover, it feeds into the Brisbane River, which has tidal characteristics. This, in turn, links to the governance and management complexities as the dam serves the interests of diverse stakeholders, who exert pressure at different levels of governance and management.

The networked nature of the reservoirs implies the need for coordinating their operations. It is impossible to discharge water from the Somerset Dam without filling the Wivenhoe Dam. Decision makers at governance and management level are therefore presented with a multifaceted problem as the solution has to satisfy more than one objective and more than one group of stakeholders.

Design time controls in the system were made ineffective by the large population growth in Brisbane, making such controls outdated and unable to cope.

On the other hand, operation time controls had to deal with a system composed of subsystems that move at different speeds. The physical perturbation to the system, i.e., the inflow of water, has a time scale of hours and is well matched by the reactiveness of the dam's operations. However, more effective operation time controls – those that should operate ahead of a catastrophic event – have been shown to belong to higher control authorities that move on a longer-term timescale of months to years.

Figure A3 in the appendix uses the York University framework [6] to report in a schematic way the above considerations.

In the case of the Brisbane flood, however, while some of the factors can be framed within a single layer, their interaction cannot be captured in this way. As becomes clear in the following section, the different speed at which the different layers moved, from many months to hours before the uncontrolled release of water, determined the catastrophic failure that the Brisbane flood is mainly remembered for.

Section 3: Discussion and transferable learnings

Looking at the structural integrity and functionality of the gates, there is little that can be imputed to the Wivenhoe and Somerset dams and their operations from 6 to 13 January 2011. However, those operations have been the focus of long investigations as the dams are the main flood mitigation devices for the city of Brisbane. This concentrated the attention on technical aspects, looking at possible engineering failures, unsuccessfully. Although left with a large degree of discretion, and with several data sources to interpret about the flood development, the engineers did what they could within what was allowed by the manual of operations to mitigate the flood. As a matter of fact, the outflow from the Wivenhoe and Somerset dams never matched or exceeded the inflow during the flood event [3].

If any early water release to free capacity were to be attempted, this should have happened in December 2010. The choice, however, to keep the reservoirs at 100% FSL determined the limited ability to mitigate the flood effects.

This was, in turn, due to the long delay between the flagging of an intense rain season and the decision on the FSL. The decision was taken on political ground, rather than technical or scientific, and it can be argued that the final decision was biased by the recent memories of the hardship caused by the Queensland's Millennium Drought (2000-2009). Nevertheless, the slow pace of the process, starting with the request for urgent advice on28 October 2010 that only received a response on 24 December, would have made any lowering of the FSL too little and/or too late.

A striking piece of evidence of the over reliance on technical solutions for complex (beyond technical) problems is apparent in the contrast between the extremely detailed guidelines from the operation manuals of the dams and the extremely vague prescribed timeline in which the decision process on the FSL is supposed to take place.

The politicisation of decision making was at the root of the discretionary discarding of three Q100 assessments higher than the current one. This allowed continued urban growth in the Brisbane flood plain. While politics has to balance conflicting instances and be able to compromise on different stakeholders' objectives, scientific assessments should be taken as inputs to policy making. In the Brisbane case, it appears that the separation between policy decisions and technical/scientific assessments was either blurred or the two were looping onto each other. Policy making is, and should be, guided by scientific evidence, but closing the loop, i.e., allowing policy to steer scientific assessments in return, introduces a complexity-enabled fragility, as highlighted by the Q100 determination in the Brisbane case.

Finally, the Brisbane/Wivenhoe case teaches us that the boundary of complex systems is not just difficult to draw on the geographical map (what dams, what catchments, what weather patterns) or on the engineering blueprints (what technical features of the dams, what element of the basin). The analysis of the Brisbane-Wivenhoe complex system, even when confined to the spatial extent between the Brisbane urbanisation and the Wivenhoe Lake, presents poorly defined time limits. These could start from the design specifications at expectations in the building of the Wivenhoe Dam (1985), as well as from the revision of the Q100 for Brisbane (1996); from the start of the Millennium Drought (2000); from the issue of the seasonal forecast for Queensland (October 2010); from the start of the torrential rain and from the (non-) decision about the FSL (December 2010); or from the declaration of the flood event (6 January 2011). The latter was chosen as the starting time point in the official flood commission report [1]. Furthermore, such a complex system presents poorly defined limits on the systems governance and management charts. This allowed for discarding scientific evidence for the new definition of Q100 but did not compel anyone to take a timely decision about the dam's FSL.

What was well defined is the sequence of operations and discretion that the dam's operators have when a flood event is declared. This appears once again to stem out of considering engineering as the solution to policy, governance and management flaws. It is now clear that, rather than looking for a single culprit, the causes of the failure lie in the cyber-physical nature of the Brisbane Wivenhoe system, that is, in the interwoven layers of physical infrastructure, their management, the political decisions that determined the Q100 for Brisbane, etc. This is the focus of the next and final section.

Generalised learning and how we can leverage it

The government of the engineering and the science of the civil government

Norbert Wiener defined Cybernetics as the study of control and communication in the animal and the machine. Before him, André-Marie Ampère used the word Cybernetique with reference to the science of civil government [7].

The term Cyber-physical systems nowadays identifies those systems where the physical components are strongly coupled to their control, which is operated, supervised or steered by humans.

The case of Wivenhoe Dam exemplifies a class of engineering systems which are, per se, conceptually simple, but become complex from the time they are inserted in a complex environment. An element that is always present in these cases is the human action, which makes most complex systems cyber-physical.

The popular image of a dam as a concrete wall might not be easily identified with a complex engineering system. However, the resulting engineering of the natural environment in which the dam sits becomes a complex engineering system and therefore must be treated as such. This changes completely the safety requirements of the system, from a purely structural angle to one of operation management. Similar considerations extend to systems large enough to impact people who feed back into the systems via political representation. In essence, any large infrastructure project can be subject to the same considerations. Examples of this are the projects currently shaping developing countries, such as the logistic corridors in East Africa, including the transport infrastructure, as well as oil ducts from South Sudan to the Kenyan coast; the Grand Ethiopian Renaissance Dam, raising the complex geo-political issue of limiting the flow of the river Nile to Egypt while being built completely outside its borders; the Gwadar port city in Pakistan, or in the developed world, the smart motorway system in Britain. All of these have the potential – and some have already proven it to be the case – to shape society, urbanisation and resource utilisation and therefore cannot be expected to deliver, and deliver safely, just by means of engineering.

Static procedures in a highly dynamic environment

The idea of static operation procedures to regulate a system in an extremely dynamic environment is a liability to the safety of the system. For such long-living systems, design-time control's effectiveness fades in time as it is dwarfed by the lifespan of the designed object.

In the case of Wivenhoe Dam, the rapid reaction and revision was relegated to the dam operations. However, when the whole system includes the urbanisation and the natural environment, the dynamic components of the system become much more heterogeneous. The increased demand for water provision in the 30 and more years of expanding urbanisation eroded the safety margins that could have provided a buffer for the contradiction in the system objectives (i.e., having the dam both full and empty). At the same time, the dam was seen as the green light to virtually unconfined urban development. In transport systems, this is known as induced demand, meaning the increase in demand for some transport modes or routes fuelled by their increased capacity. While engineering cannot solve this fundamentally social problem, the use of common infrastructure, it can indeed help by supporting existing assets with demand management strategies, which are at the heart of systems engineering. As with every ecosystem, the built environment has to fare within the resources available, meaning that managing infrastructure's user load can be considered as the built environment equivalent of thriving within the resources of the natural environment. This could be achieved by implementing control and feedback strategies to include the users in the design and management process. The alternative is the reactive fashion with which policy has invested the engineering of the iterative solutions of iteratively generated problems. Unfortunately, such an alternative is flawed.

The challenge of dynamical systems in a highly dynamical and uncertain environment

Having the cyber (intended as human) and physical (intended as hard infrastructure) parts of a system efficiently working together presents as many challenges as opportunities. The challenges of defining the FSL as early as October for the Wivenhoe Dam is comparable to allocating space in refrigerated warehouses for the food supply chain or to secure stocks of personal protection equipment for health operators. While accountability requires a human sign-off, decision support tools may, and should, stay separate from human biases. A decision support tool that, on a day-by-day basis, forecasts a dam's FSL (not just the level) or a warehouse's floorspace would face the challenge of integrating the right information in the right amount, which would still imply human decisional intervention. Yet, achieving such a level of unbiased directions would enable accountability across the system with neater contours than is currently possible.

Complex systems, when considered holistically, are evolving systems [13]: the time factor is pivotal. The image of the giant, monolithic Wivenhoe Dam as an engineered artefact, static in space and time, is in this sense deceiving. As soon as we extend the system to the natural and built environments surrounding the dam, the stakeholders, the governance and management, the imposing Wivenhoe Dam is scaled down from the system to a component of it. Strikingly, the engineered artefact is likely to become the most static part of all the system components. Every other component in the system moves, changes and gets transformed in time. Capturing these parallel evolution patterns and how they impact on the entire system can be the key to safer complex engineering systems.

Appendix

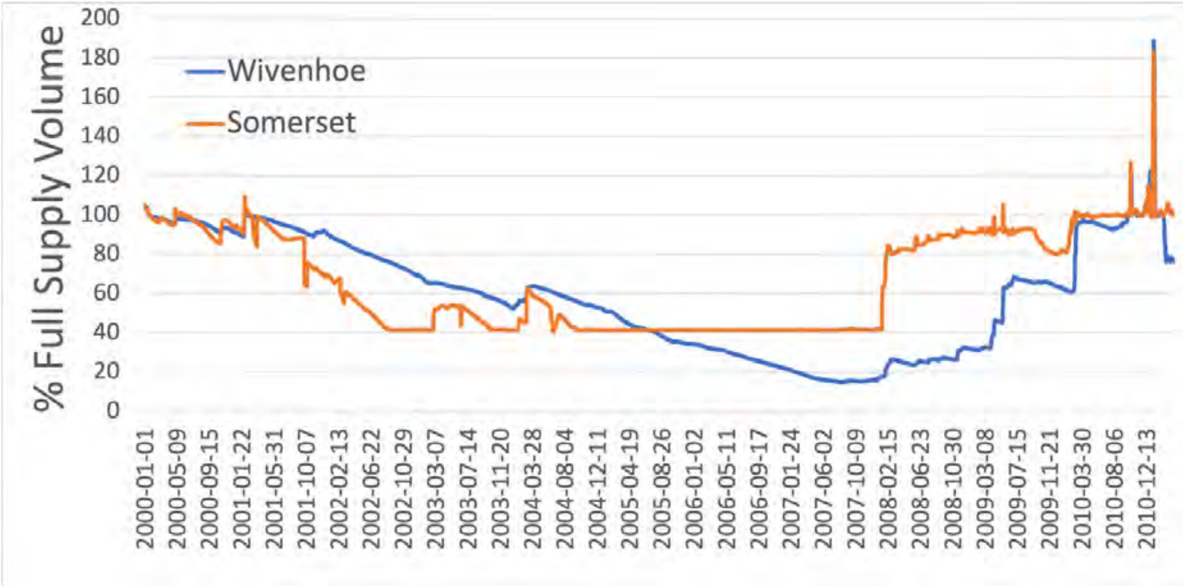

Figure A1: Percentage of full supply volume for the Brisbane and Wivenhoe dams from the start of the Millennium Drought (200) to March 2011. Note the reduction in volume decided for the Wivenhoe dam after the 2011 Brisbane flood to the right of the diagram. Data by Seqwater.

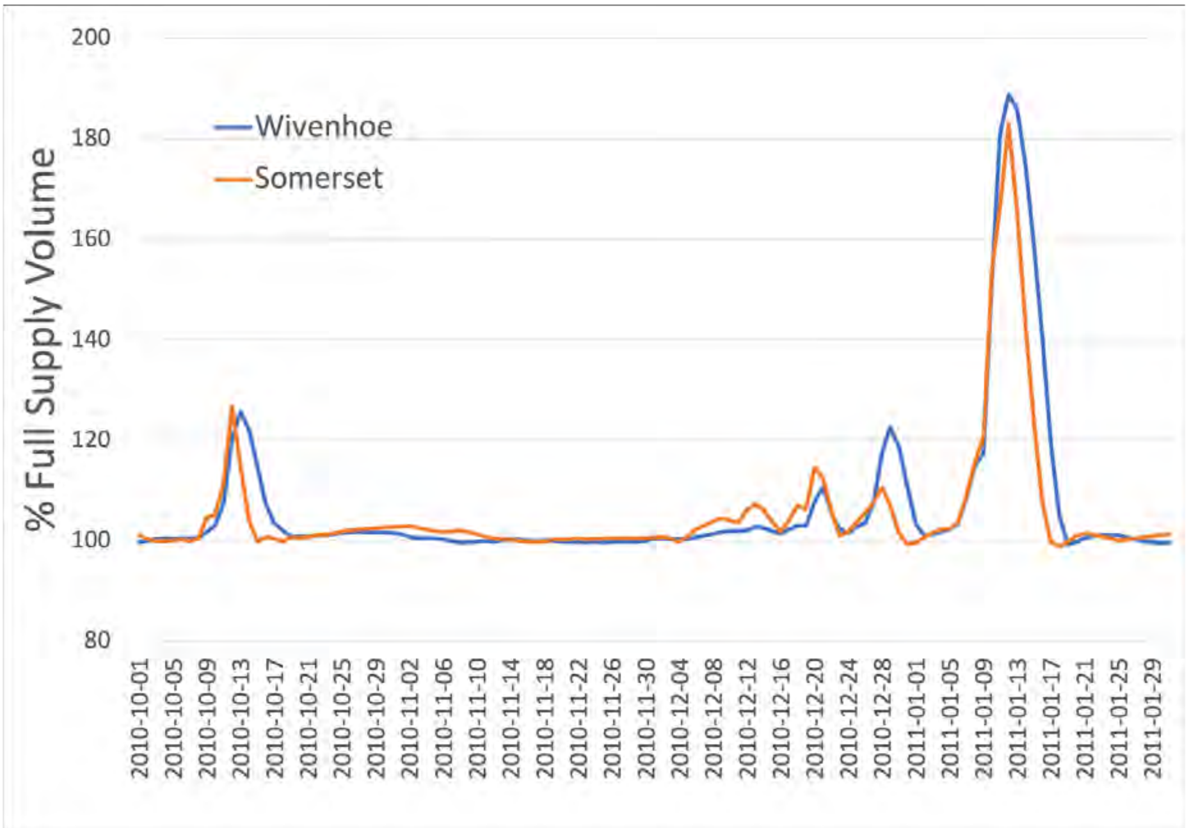

Figure A2: Percentage of full supply volume for the Brisbane and Wivenhoe dams from October 2010 to January 2011. Data by Seqwater.

COMPLEX SYSTEM SAFETY FRAMEWORK FOR THE 2011 BRISBANE FLOOD

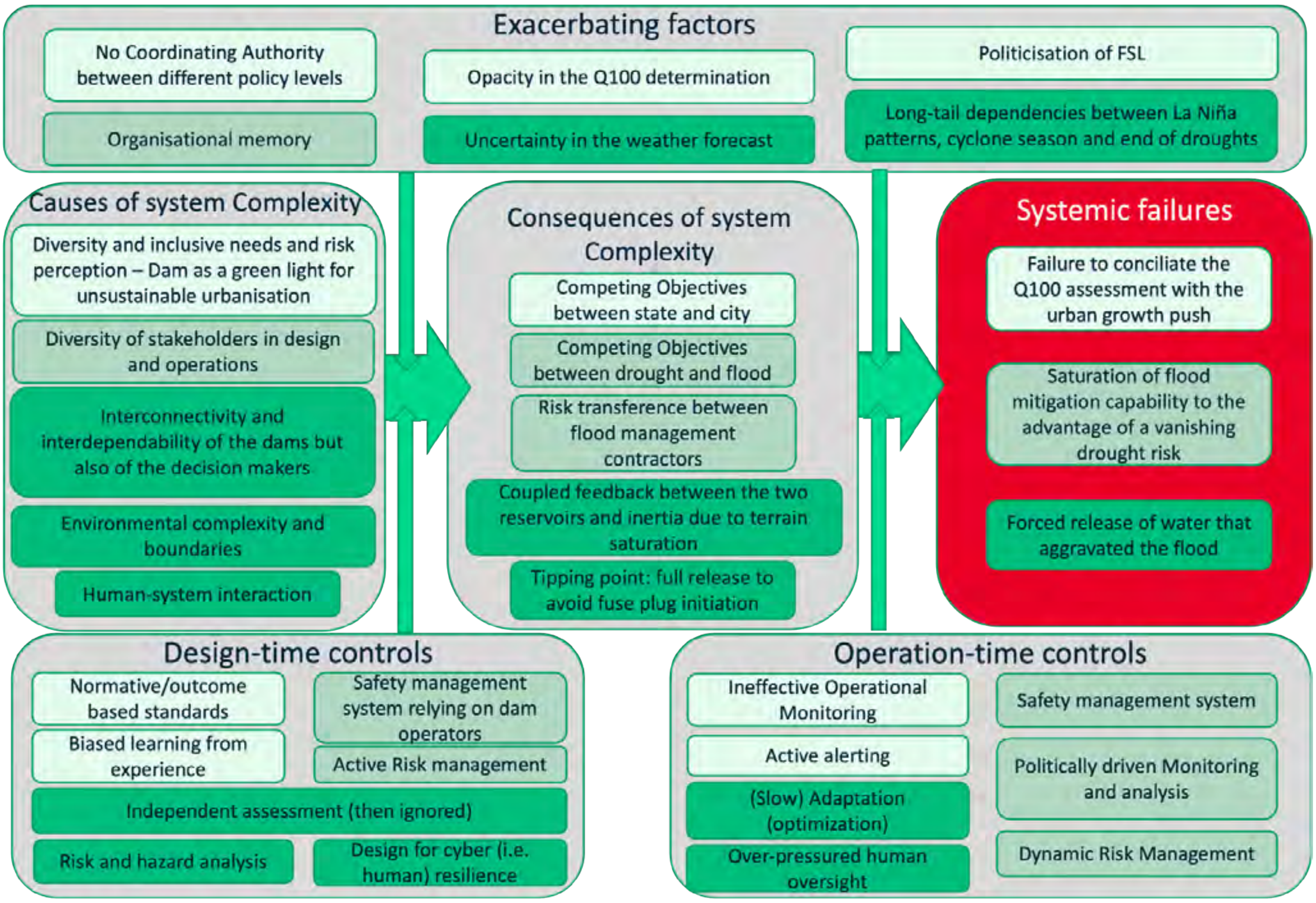

Figure A3: Complex system safety framework, as developed by the University of York [6], applied to the case of the 2011 Brisbane flood. The three shades of green correspond, from pale to dark, to the governance, management and task/technical layers to which the different factors/approaches belong. The framework groups the factors in 'elements', here, represented as boxes with a grey shade.

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Australian climate extremes and building transport network resilience

By Dr Kristen MacAskill, Dr Marlies Barendrecht, Dr Catherine Tilley

Executive summary: This case investigates the role of the Queensland Reconstruction Authority (QRA) in improving resilience of the road network in Queensland, Australia, following floods in 2010-11. Over ten years the QRA's remit expanded from oversight of asset repair to include longer-term hazard exposure concerns and community-oriented initiatives. Capabilities (developed in response to a crisis) have been maintained through the QRA transitioning from a temporary to a permanent entity.

Tags: Tropical Cyclone Yasi, transport, road network, regional crisis, local community, resilience theory, flood risk, technical and adaptive change, Cynefin framework, capacity-building

Section 1. Background and introduction

Infrastructure system resilience requires not just engineering design expertise, but also an understanding of exposure to hazards, how that exposure is changing, and how the rules governing decisions determine certain outcomes. This case study focuses on the implications of this for transport infrastructure, with a primary focus on roads. It covers a series of major flood events and their impact on the evolution of disaster risk governance and the resilience of road infrastructure in Queensland, Australia.

The case presents the need to adopt a systems approach to safety in addition to more traditional engineering concepts of safety. Traditional road transport safety focuses on how asset design and management minimise accident frequency/severity on the road itself. While systems thinking has been incorporated into transport safety in recent decades, this case takes the concept further. It adopts a socio-technical systems perspective that considers the criticality of the service provided: community survivability and resilience is fundamentally linked to the availability and functioning of transport connections.

Australia often hits global news headlines with climate extremes – droughts, fires and floods. Extended drought in the early 2000s led to major investment in water treatment and recycling systems. This period was immediately followed by major flooding in 2010-11. The extent of damage caused by this flooding resulted in the establishment of the Queensland Reconstruction Authority (QRA) to fill a major capacity gap in the management of a state-wide reconstruction process. The establishment and evolution of the role of the QRA provides a case for exploring the evolution and advancement of disaster risk governance and the implications for how critical transport assets are managed. A more detailed description of what happened in Queensland and the approach to creating this case study is available in the longer version of this research, which presents more detailed evidence.

> *"We can't stop these floods. The scale of them is beyond the resources of government to deal with. So, we are a flood city. We're a River City. We'll forever remain that way. So, let's accept that and not pretend that someone is coming in on their white shiny horse [to] build … some kind of hard engineering solution here that's going to fix the problem. And working that through with the community to get that acceptance, [we can] then talk about: 'Well, what can we do to adapt or to reduce the consequence?' which was sort of the start of our journey on resilience." (Case study interviewee)*

Context

Queensland, Australia, has a population of approximately five million people (Australian Bureau of Statistics, 2020a) and an area of 1.7 million km^2, more than seven times the size of the United Kingdom. Of the total population of Queensland, 64% lives in the (mainly coastal) cities and the rest in rural areas (Australian Bureau of Statistics, 2020b). The state has over 183,000 km of roads (Department of Transport and Main Roads, n.d.) of which 18% is managed by the state's Department for Transport and Main Roads (DTMR) (Queensland Government, n.d.) (see **Figure 1**).

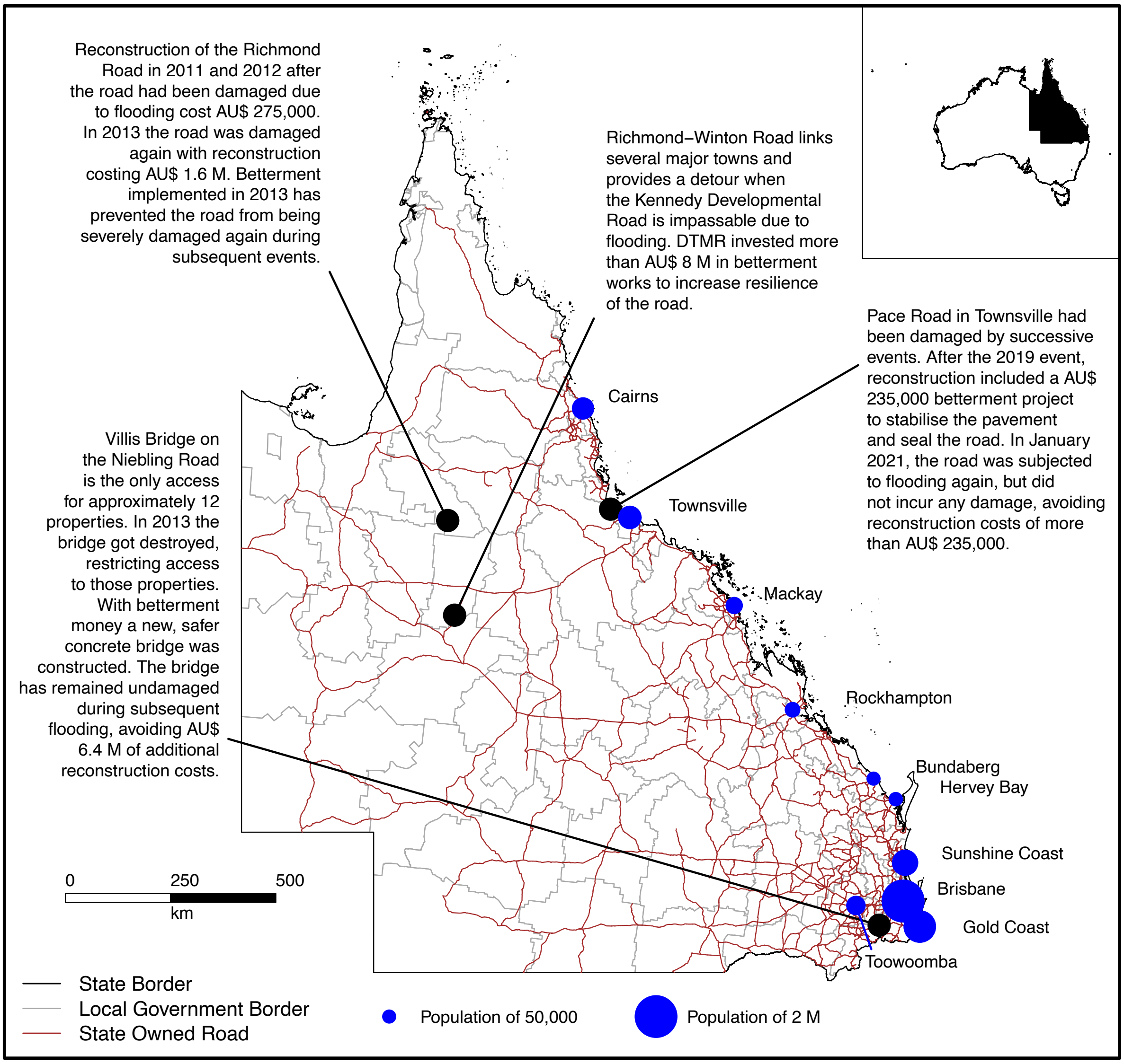

Figure 1. State owned road network of Queensland, Australia. Red lines represent state owned roads. Grey lines represent local government borders. The 10 biggest cities/towns in Queensland are shown (with a population of 50 thousand or higher). Annotations provide select examples of recovery interventions that include build back better (betterment) of the transport infrastructure system. For reference: AU$ 1 is approximately £ 0.54. Sources: State of Queensland (Department of Resources), 2021a (state road network); Australian Bureau of Statistics, 2011 (country borders); State of Queensland (Department of Resources), 2021b (state borders); State of Queensland (Department of Resources), 2021c (local government borders); Queensland Reconstruction Authority, n.d. (betterment case studies).

The climate in Queensland varies from tropical to very dry and the state has a long record of droughts and floods. After a long period of drought, flood events in 2010/11 resulted in unprecedented damage estimated at AU$ 15.7 billion (approximately £8 billion) across the entire state (World Bank and Queensland Reconstruction Authority, 2011). In response to this event the QRA was established as a temporary organisation to oversee the reconstruction process. The QRA was given the mandate to distribute funds made available by the national and state government. The QRA's task was to deliver this funding to local councils who had assets in need of repair or reconstruction and to provide coordination and efficiency that could not be achieved by the councils managing their individual programmes alone.

Over the past decade, the way in which the QRA undertakes its role has evolved. It started out by managing reconstruction projects, focusing on repair and returning the road network to a condition that resembled pre-disaster function. This was predominately driven by the rules surrounding the allocation of federal funding. The QRA's remit was then expanded to allow greater scope for increasing robustness through the introduction of a build back better fund. More recently, the remit was expanded even further following the QRA's establishment as a permanent entity. It has since become more involved in community resilience-building initiatives. **Figure 2** provides an overview of the events and changes that have occurred, as well as the development in knowledge that were necessary to facilitate these changes (explained further in the next section). The development of activity can be characterised through changes in the system boundaries of QRA's remit, reflected in the 'system intervention' in **Figure 2**.

We adopt a version of Snowden and Boone's (2007) Cynefin framework to explain the nature of this changing remit[1]. Initially the system of intervention for QRA consisted mainly of the road network assets. Following an initial period of 'chaos' in establishing the organisation during a response phase, we suggest that the organisation settled into something that could be classified as a 'complicated' operating basis. Expert engineering knowledge was necessary to develop solutions for reconstruction and the solutions were mainly technical interventions (for example reinstating road pavements).

Over ten years the QRA's system of intervention has expanded to include wider considerations for the environment (such as the future threat of natural hazards) and communities. This goes beyond the initial mandate of recovery programme coordination and involves a more 'complex' operational context. This requires different types of knowledge and there are not always obvious engineered solutions to problems. These developments were the result of repeated experience of flooding and the associated learning and capacity building that resulted from that. The repeated experience also provided the political will to look for more holistic approaches towards the management of flood risk (**Figure 3**).

Section 2: Analysis and insights

In this section we examine three key themes in the evolution of resilience management of transport infrastructure in Queensland and the role of the QRA. While these themes can be considered separately, they are closely linked, and their combination has been important for Queensland's path to improving its disaster resilience. Key learnings from this case can be drawn through these themes.

The Queensland Reconstruction Authority as a resilience broker

The formation of the QRA led to a process of transition in managing checks and balances of disaster recovery at a local, state and national level. The QRA had to engage local governments to help them in that transition and, at the same time, had to show the Australian Government that they knew what they were doing. From the start the QRA worked to build relationships and trust with the local, regional and national levels of government. These relationships allowed them to act as a broker for building resilience in two directions. From the top down, they receive lump sum funding from the national

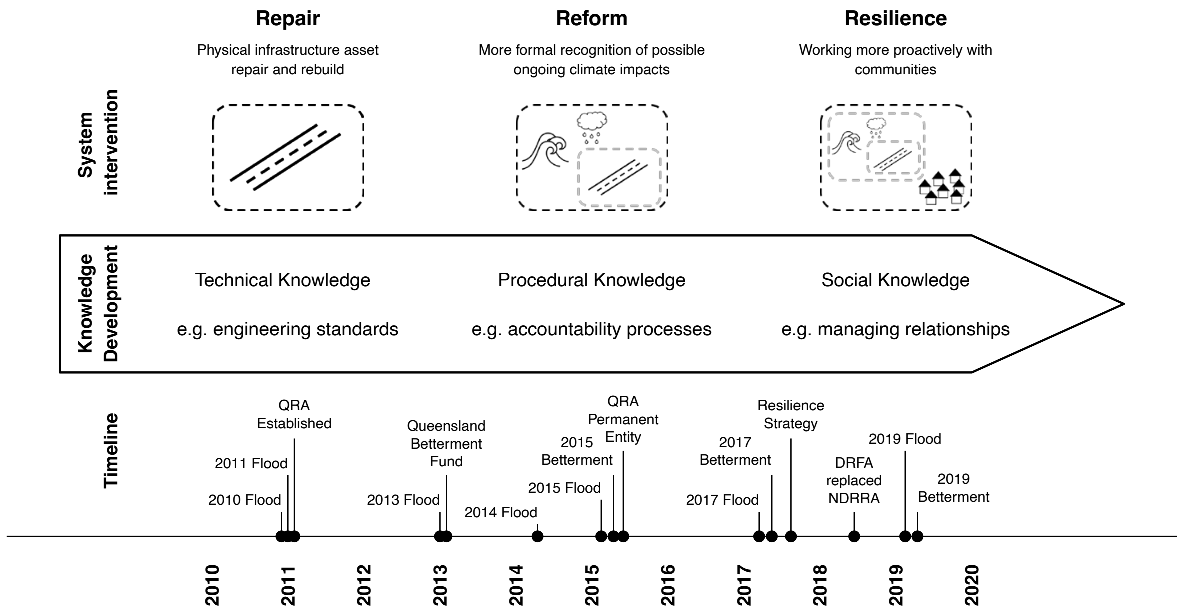

Figure 2. Timeline of events in Queensland that led to changes in QRA's responsibilities.
The figure shows the changes in the system encompassed by the QRA's remit, as well as the development of knowledge over the past decade. The timeline shows the most important events and only includes the most severe flood events. DRFA = Disaster Recovery Funding Arrangements, which replaced the NDRRA: Natural Disaster Relief and Recovery Arrangements.

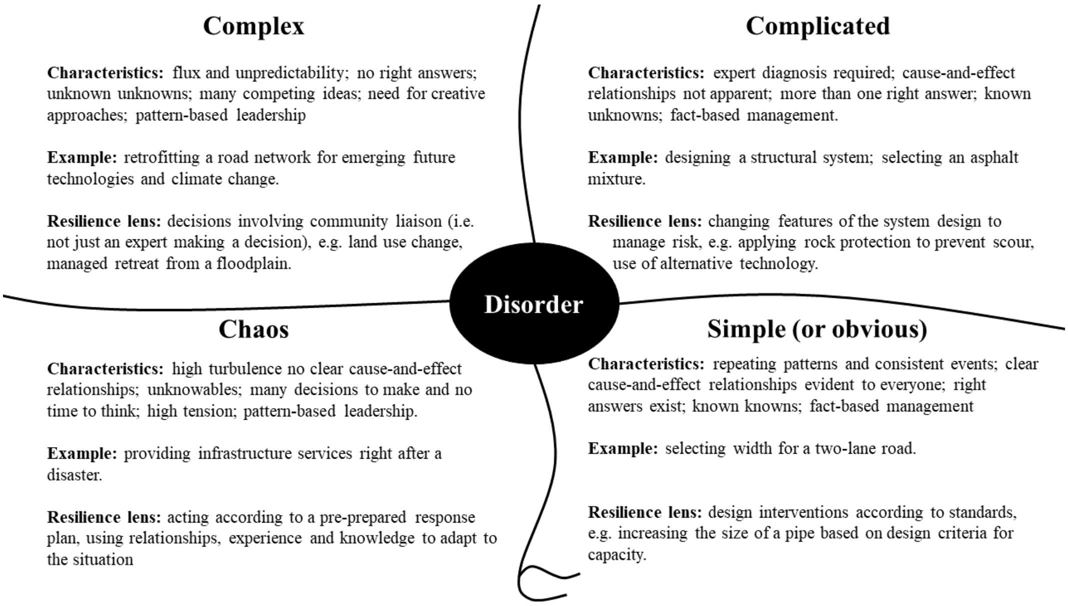

Figure 3. The Cynefin framework applied to road infrastructure decisions. Each domain has different characteristics and requires a different approach to management. Also, the approach to managing resilience varies depending on the domain. Adapted from Snowden and Boone (2007) and Chester et al (2019) and a hierarchy of resilience measures presented by MacAskill & Guthrie (2015).

and state government, who place trust in the QRA to distribute that funding to local governments in an efficient and effective manner. From the bottom up, the local councils appeal to the QRA for changes in policies and funding arrangements. They share their needs with the QRA and the QRA can advocate for change at a regional and national level. One example is the Betterment Fund, which was called for by local governments, advocated for by the QRA and eventually funded by the Australian and Queensland Governments.

The ability of the QRA to act as a resilience broker can be summarised by some key characteristics of the QRA as an organisation:

1. It has a mix of permanent employees and temporary employees from government departments and contractors. It draws on knowledge from both the public and private sectors and distributes that knowledge to local governments, when and where needed. It can scale its operation up and down to meet demand.
2. It facilitates resilience-building by bringing people together. Local forums have expanded into regional strategy development activity.
3. It has the financial capacity to take on risks for initiatives where there are potential wider benefits to be gained through shared learning. Together with local councils, the QRA facilitates the implementation of new plans and new solutions. This has been aided by the support of the state and national government.
4. The QRA has demonstrated the ability to operate within the legal bounds and evidence-base requirements. At the same time, it has built relationships with the local councils, allowing them to implement new projects and ideas with their cooperation.

The relationships are not always smooth. While local government representatives express appreciation for their relationship with QRA, there is also some discontent. This is associated with (A) the added burden of processes developed for claiming compensation and (B) local coordination does not extend to the established local presence of the QRA in more remote regions.

Funding Arrangements

Recovering from a severe flood event may require redistribution of money across different levels of government as the costs can be well beyond a local government's financial capacity to manage. This is where special recovery financial mechanisms come into play, often involving national government subsidy of local costs. There are several ways in which the availability of funding and the arrangements surrounding the distribution of funding can hinder or facilitate resilience building. Queensland's experience provides some examples:

1. The main recovery funding provision in Queensland did not, until recently, provide for betterment. A separate line of funding for betterment existed but was practically inaccessible. This limited the options for improving the robustness of assets when the QRA set out to manage reconstruction after the

2010/11 floods. However, building on the experiences of managing repeated flooding, it was able to negotiate a new funding mechanism. From 2013 onwards the Queensland Betterment Fund allowed for 'building back better' by increasing the robustness of infrastructure assets with respect to flooding (See **Figure 1** and **Figure 4** for examples). In addition, the new Disaster Recovery Funding Arrangements (DRFA) introduced in 2018 provide an opportunity for reconstruction programme savings to be spent on other preparedness and resilience-building initiatives.

2. Allowing local councils to implement the reconstruction work can result in efficiencies and, under the new DFRA, can help save money that can be used for resilience building. Put in other words: paying the local government to do the work is resulting in savings that can be spent on other projects.
3. A related financial factor is the capacity of local councils to invest early to mitigate flood risk. It is generally accepted as impractical to engineer a solution to fully prevent flood damage and achieve an absolute level of safety. Instead, there is an acceptance of the need for communities to cope with some level of flooding. The local councils recognise the need for improving community resilience and the funding made available for these purposes (via the QRA's wider resilience agenda) has been used for a variety of information campaigns.

This case shows that, in the short term, revising funding arrangements can help remove barriers to resilience building. This has been implemented with the aid of the QRA. However, limitations remain and there is ongoing debate over finding a balance in investing across mitigation, preparedness and recovery. The benefits of resilience building are not easily captured in standard cost-benefit analysis processes.

Explicit and tacit knowledge

One of the key capabilities that the QRA has developed over the past decade is knowledge acquisition. Here we make a distinction between two types of knowledge the QRA has gathered and developed: explicit knowledge (design standards and evidence of flood damage) and tacit knowledge (managing social relationships).

The QRA has accumulated extensive knowledge on the state of the road transport network. It set up a database containing damage and repair data that has been gathered through local councils and the DTMR. This has helped resilience building in Queensland in several ways. It provides evidence for funding claims, enabling more transparent claims management. It also provides the QRA with the evidence to make a case for changes in funding arrangements, such as in the case of the Queensland Betterment Fund. Finally, the database allows for a more comprehensive analysis of the state of the transport network than existed before. This can assist in finding vulnerable points in the network.

Tacit knowledge also developed over time. When established in 2011, the QRA focused on repairing assets. It was responsible for overseeing the distribution of funding and, as a result, developed knowledge on how to effectively manage a state-wide programme (for example it developed and implemented processes for funding applications and approvals, including the development of online platforms). The QRA also developed new networks and became knowledgeable in managing the relationships with local councils, state agencies and the federal government. When its remit expanded to include community resilience, its experiential knowledge expanded to creating awareness raising campaigns and increasing community preparedness. Thus, throughout

Figure 4: Aurukun Access Road (the only road link to and from the Aurukun community). Left: Gravel road that was damaged in 2010, 2011, 2012 and 2013. Right: Bitumen seal instated in 2013 along a 10 km vulnerable section. This has since withstood the impacts of eight natural hazard events (photos courtesy of QRA).

the past decade the QRA acquired knowledge with very different characteristics: from technical, to financial management, to social and cultural.

Section 3: Discussion and transferable learnings

This case study calls for management approaches that go beyond a mindset that focuses on infrastructure as a complicated system to an approach that engages more holistically with the complexity associated with the infrastructure system as a service. While the context for this case study is specific, there are some observations that may be generalisable to other organisations seeking to improve societal resilience.

There are two distinct types of change within this case study: technical and adaptive (Heifetz & Linsky 2002). The QRA began its work facilitating technical changes, such as improving the engineering standards and advocating to change eligibility requirements for rebuilding roads and bridges. Repeated flooding resulted in repeated damage, helping to create the business case for going beyond restoration to a former state (through repairs and treating the problem as 'complicated'). To build resilience in the system, the QRA had to take an adaptive approach to leadership – redefining and expanding its interventions in a way that is reflective of managing complex problems. The QRA began this work as a perceived natural extension of its activity, although there was no formal mandate to do so.

This process of adaptive change had several distinctive features. First, there has been a multi-year process of engagement with local communities. This has allowed the QRA to build social connections across the system so that it can understand local needs and help build local capacity. Although there is some centralised expertise in the system, there is an important role for the local communities themselves to develop responses to flooding in their area. Second, the development of a database of damage and repair information means that people from across the system have a shared way of seeing the network, despite there being hundreds of miles of distance between stakeholders. This combination of activities means that the QRA has made the network socially denser—in effect, more complex—but at the same time has made it easier to understand its characteristics.

This added social complexity may seem counter intuitive. Often, added complexity in an organisation is seen as more difficult to manage and more costly. Very often, we approach problems by simplifying them first – and yet that was clearly not the approach to change here. In this case, the complexity was helpful because it created value in parts of the system: for example, the closer relationships between the QRA and the communities enabled initially a more effective and timely allocation of funds and, later, an ability to build capacity at local level. The relationship between the QRA and the Australian Government allowed the system to allocate funds in line with policy and with clear accountabilities. The QRA thus created a key mediating role, in a way creating more complexity in the network, but also adding the necessary capability to achieve wider success in disaster risk management.

While QRA was introduced as a new entity, it essentially slotted within the existing hierarchical governance system. The national and state governments decided to make money available and exercised their power to give the QRA the mandate to distribute that money. The QRA's power to approve funding for local projects is bound by the legislation and guidelines set within this system.

In conclusion, the way in which the QRA worked to build resilience to flooding in Queensland's Road network was characterised by:

1. Creating a knowledge base to ensure that 'technical' problems could be resolved to an appropriate standard, more consistently.
2. Adding density to the social fabric of the system as a way to 'shorten the distance' between national and state government and local communities and to provide a way to transmit knowledge between groups. The QRA achieved this by building its network with the local communities early in the process and in parallel with technical problem-solving.
3. Expanding its remit beyond an asset reconstruction programme to engaging in capacity-building, despite the added complexity this brings to defining what success looks like for its own operations
4. Managing the tensions that arise from differing interests and priorities across the system.

To do this, leaders need to be able to understand multiple points of view, to pay close attention to stakeholders and to be more invested in solving problems than in 'being right'. These capabilities are relevant in a broad range of situations where the safety of a complex system involves behavioural as well as technical components.

List of acronyms

DTMR	Department of Transport and Main Roads
DRFA	Disaster Recovery Funding Arrangements
NDRRA	Natural Disaster Relief and Recovery Arrangements
QRA	Queensland Reconstruction Authority

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Endnotes

1. The Cynefin framework is a descriptive rather than a diagnostic framework, helpful in this case for describing the evolution of decision-making in Queensland over time.

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Planned Adaptive Regulation: Learnings from the Delta Programme

By Dr Richard Judge, Prof Arthur Petersen

Executive summary: Planned adaptive regulatory methods (PAR) offer considerable potential as a way of tackling significant uncertainties – such as those arising from rapidly advancing innovations or from multi-decade time horizons. The Dutch Delta Programme, grounded in adaptive management approaches, shows what can be achieved. It provides valuable transferable experience of both the benefits and the implementation challenges for PAR.

Tags: regulatory systems, governance, adaptive methods, risk management, flood protection, freshwater supply resilience, spatial planning, climate change, innovation, The Netherlands

Section 1: Background and introduction

Many people will know the tale of the Dutch boy who noticed the sea trickling in through a small hole in a dyke and averted disaster by plugging the hole with his finger[1]. The real-life equivalent took place during the 1953 North Sea Flood. Arie Evegroen used his grain barge to plug a large hole in the dyke along the river IJssel and reportedly saved the town of Nieuwerkerk from flooding.[2]

Others were less fortunate. On 31 January 1953, an extreme combination of a high spring tide, heavy rainfall and a severe windstorm over the North Sea caused an area of more than 1500 km^2 to flood. Coupled with a combination of human errors and technical failures (see **Box 1**), this storm cost many lives[3,4] – 1,836 people died in the Netherlands, 72,000 people lost their homes, 30,000 livestock were lost, with a 0.7 bn Euros cost to the Dutch economy (about 10% of GDP).

Box 1: The 1953 *Watersnoodramp* (flood disaster)

Human errors & technical failures combined to cost lives:

- Weak spots from inadequate maintenance led to over 65 breaches of protective dykes in SW Holland.
- As coastal dykes collapsed, flood waters then hit and broke through inland dykes.
- This domino effect meant that communities faced water levels rising up to 3m within hours.
- The scale and unexpected nature of the disaster meant that warning systems were ineffective.
- Local alarms sounded by church bells failed because use was not sufficiently ingrained in daily lives.
- Rescue efforts took several days to develop fully.

The 1953 *watersnoodramp* (flood disaster) led to a major rethink of coastal defences, weather prediction and flood warning systems in the Netherlands. This resulted in the creation of the Delta Works (**Figure 1**), an enormous and innovative series of flood defences built over several decades at a cost close to 5 bn Euros.

However physical infrastructure forms only part of the picture. Actions to develop equally critical but intangible infrastructures have been an important part of the response. These actions include extensive investment in research and capability to build and apply knowledge, evolution of the institutional frameworks to strengthen governance and sustained stakeholder engagement.

This case study outlines how the Netherlands shifted from protecting themselves from immediate threats of flooding to a more forward-looking system able to adapt to future challenges (such as climate change). The case focuses on the Delta Programme's adaptive management approaches, which are designed to cope with the significant uncertainties that multi-decade timelines bring. The experience is transferable to the governance of other complex projects and innovations, in particular to the development and application of 'Planned Adaptive Regulation'.

Section 2: Analysis and insights

The Delta Programme

The primary purpose of the Delta Programme is to ensure that the

Figure 1: The Delta Works, a €5 billion, 30-year programme of flood defences consisting of levees, dikes, dams, sluices and storm surge barriers. Many new structures were built, together with reinforcement / upgrade of existing defences. a) map of Delta Works. b) 1958 – storm surge barrier in the river Hollandse Ijssel. c) 1986 – storm surge barrier in Eastern Schelde. (Source: Rijkswaterstaat via [5])

Netherlands is protected from flooding and freshwater shortages — now and for the foreseeable future.

While this core purpose has remained constant, the detail has changed in many ways since its inception in the 1950s. The Delta Programme's priorities are captured in the Delta Decisions[6] published in 2014 (refreshed 2021). These set out the overarching policy framework for flood risk management, freshwater supply and spatial planning that is climate-proof and water-resilient.

The governance system

The approach to governance has been informed by two Delta Commissions: the first set up shortly after the 1953 floods; the second in 2007. Key developments are identified in **Figure 2**.

With almost a third of its land below sea level, Dutch communities have a long history of strengthening natural sea and river protection by creating and maintaining artificial barriers, controlling inland waterways and caring for reclaimed land (the polders). Current approaches to governance build on institutional frameworks and collaborative models that have long been instrumental in protecting the Netherlands. This includes an on-going role for district water-boards that have been at the heart of Dutch water management activities since the 13th century.

Figure 3 provides an overview of the many organisations involved in the governance system and the responsibilities of key actors (central government, district water-boards, Rijkswaterstaat and the Delta Commissioner). The boundaries of this system align to the Delta Programme's water management responsibilities (with its inter-dependent tasks of flood protection, freshwater supply and spatial planning). In practice, interconnections are also needed with other infrastructures, activities and communities that interact with the Programme (such as inland shipping or fisheries).

System complexities

The 1953 disaster brought to life the complex interplay between interconnected physical, natural and social systems. It showed failures rapidly cascading and escalating, as breaches in primary coastal defences led to failures in secondary dyke systems. Although many of the risks had been foreseen, it was this disaster that brought the political consensus and funding needed for action.

Flooding in the 1990s highlighted the need for sustained vigilance and for anticipating future issues in sufficient time to prepare. The multi-decade timeframes involved bring significant uncertainties:

- Emerging engineering knowledge (such as dyke failure mechanisms) and technologies;
- Impacts of climate change (such as sea levels rising and land mass falling);
- Socio-economic changes (such as population growth and urban development);

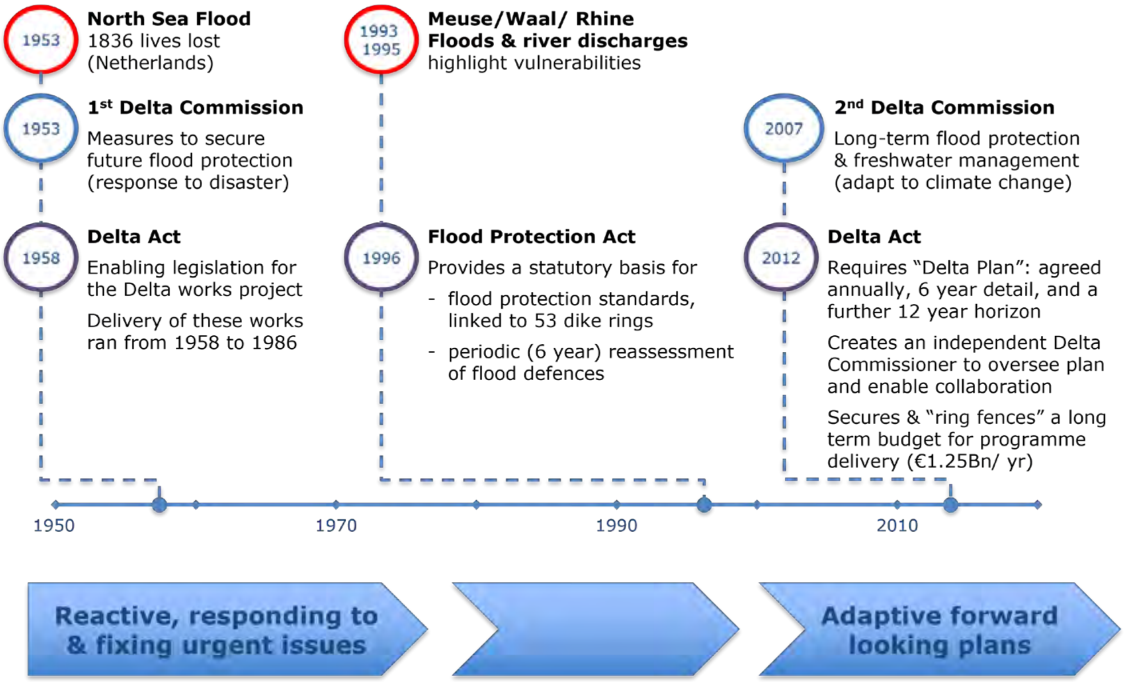

Figure 2: Evolution of approaches

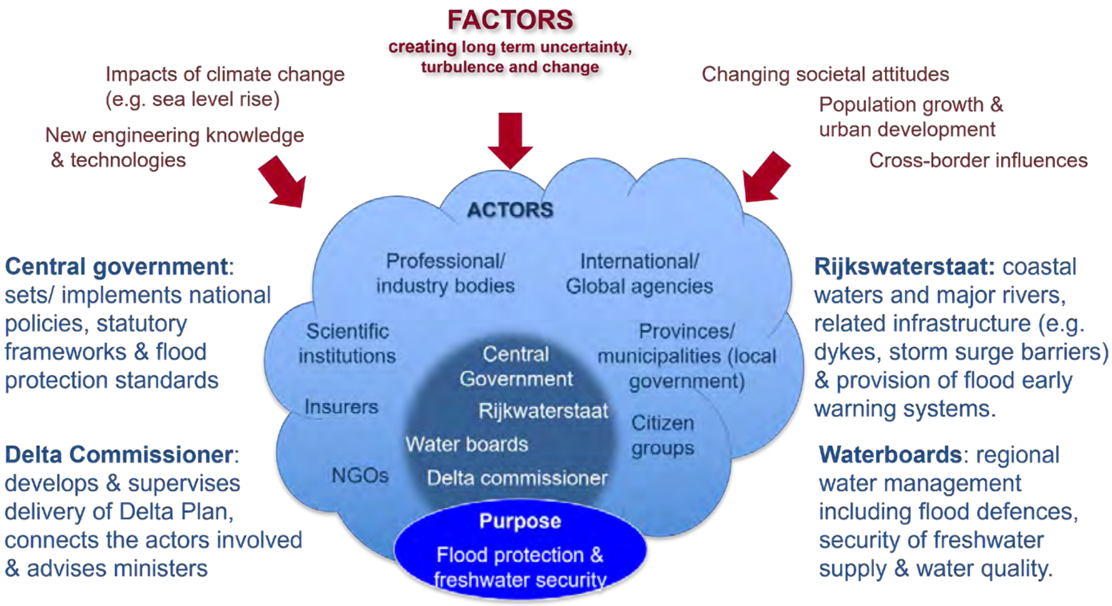

Figure 3: The governance system and its context. (Adapted from [7])

- Cross-border influences (such as the impacts of decisions taken upstream by other nations);
- Changing societal attitudes (adding unpredictability to political choices and trade-offs).

Adaptive Delta Management

The importance of adaptive policymaking was emphasised by the second Delta Commission and in the ensuing Delta Programme. The concept of Adaptive Delta Management was introduced as a way of dealing with the uncertainties of multi-decade timeframes. This shifted the emphasis from reaction to anticipation and adaptation: from reacting to issues flagged by periodic reassessments to anticipating possible futures and putting in place mechanisms that enable flexible responses.

Accompanying timeframes reflect the long-term horizon: six-year review cycles for strategic decisions; allowing until 2050 to implement infrastructure improvements; research to inform major choices beyond 2050 (for example on sea level rise).

Associated governance practices draw on five strongly inter-related elements: institutional mechanisms; flood standards; anticipatory mechanisms; systematic monitoring and feedback; and stakeholder engagement. Each is described below.

Institutional mechanisms

The typically short-term nature of political decision-making can present a particular challenge when addressing long-term issues. The 2012 Delta Act included three 'policy commitment devices' to sustain long-term focus. These:

- Required the development, periodic review and annual presentation to Parliament of a Delta Programme that addresses future risks to floods and freshwater supplies.
- Secured long-term funding for development and delivery of the Delta Plan, and associated research activities, through the Delta Fund (averaging €1.25 bn / year until 2032).
- Formalised the role of an independent Delta Commissioner[8] to oversee and connect the multiple governmental layers and stakeholders involved. The Commissioner informs and supervises delivery of the Delta Programme, taking a systems perspective that ensures cohesion between its component parts and connects short-term decisions to long-term goals. The Commissioner does not have formal decision-making authorities, but instead relies on influence through their powers: to convene, facilitate and catalyse stakeholder actions; to report directly to parliament; and to draft the yearly investment programme.

The independence of the Delta Commissioner, together with funding to support knowledge development, reinforces the separation between those advising on what is needed and those elsewhere in government formally responsible for decision-making and implementation.

Flood defence standards

Safety standards for coastal flood protection were established in the 1950s (by the first Delta Commission) and for rivers in the 1970s. Protection levels for each of the 53 uninterrupted rings of water defences (dyke rings) were formalised by statute in the 1995 Flood Protection Act.

Fundamental changes to flood protection standards were introduced in 2017, building on more than a decade of underlying research and studies. These shifted focus from the probability of a flood exceeding the height of the dyke to the probability of an individual losing their life due to flooding. Making the standards more outcome focussed brings a number of advantages[9]:

- It shifts the focus from 'hazard' to 'vulnerability', which also helps provide a stronger rationale for adaptive methods;
- It takes account of the many advances in probabilistic tools over recent decades, such as methods to include uncertainties in design assessments and extensive relevant data;
- It allows for different dyke failure modes (beyond water levels exceeding dyke heights), including those indirect modes that may be linked to maintenance or inspection issues;
- It enables greater granularity than dyke rings. The standards ensure consistency across different areas (with a minimum protection level for individual fatalities at 1:100,000 per annum) and the option of enhancing protection in specific areas (such as critical infrastructure);
- It opens the option of a multi-layered flood strategy, including prevention, flood resilient spatial planning and crisis management. For example, the standards can be achieved by avoiding the risk (building on higher ground) or by effective response (reliable and robust evacuation strategies).

In introducing these standards, a specific challenge has been to develop the software and other assessment tools that make sophisticated assessments more readily usable by non-experts.

Anticipatory mechanisms (adaptation pathways)

Adaptation pathways use a combination of systems analysis, storylines and scenarios to describe and plan for future developments. They step forward in time from current conditions to describe the evolving impacts of changing physical, natural or socio-economic conditions, as well as showing how responses to these impacts can themselves affect the changing conditions (**Figure 4**). Examples of adaptation pathways developed for the Delta Programme is detail in their 2014 report[10].

These methods provided insight into policy options, the sequencing of actions over time, potential lock-ins and path dependencies. Importantly, they also highlighted 'tipping points' – those future points in time when actions are needed to avoid system failure. A total of 14 pathways, with a planning horizon until 2100, provide the basis for regional strategies, actionable plans and a committed budget allocation averaging €1.25 bn / year until 2032.

Explicitly acknowledging uncertainty and knowledge gaps brought wider benefits. The adaptation pathway diagrams helped to raise awareness about the issues faced, allowed people to visualise multiple alternatives and provided political support for keeping long-term options open. They were seen as a useful way of communicating concepts and attracting stakeholder support. The added transparency also motivated policymakers, politicians and other decision-makers to

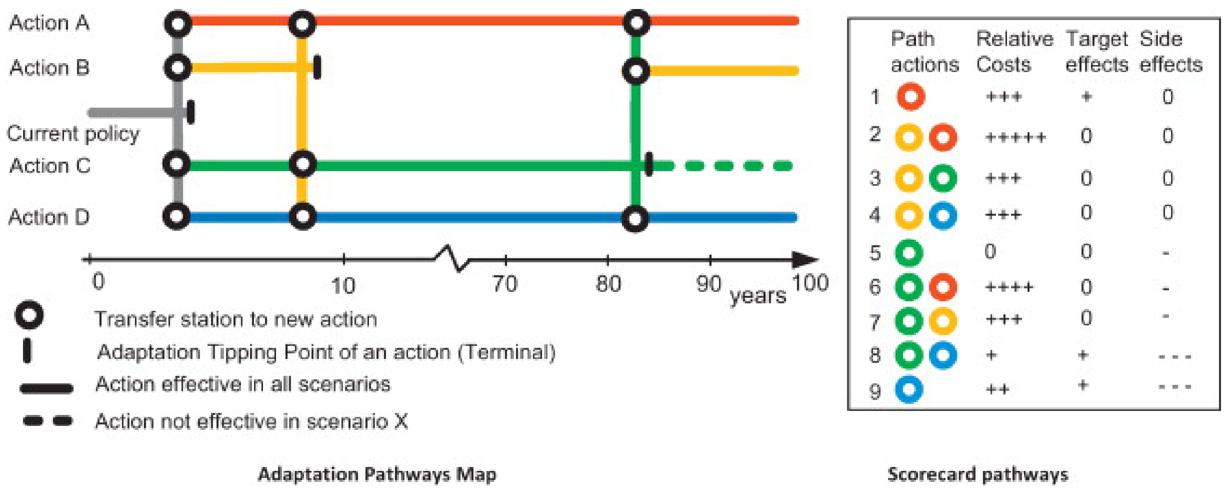

Figure 4: Generic map of adaptation pathways. Starting from today, targets begin to be missed after 4 years. There are four options: Actions A and D achieve the targets for the next 100 years in all scenarios; Action B reaches a tipping point at about 9 years. A shift to one of the other actions will be needed; Action C achieves the targets for the next 100 years for most scenarios (but not Scenario X); However, under Scenario X, Action C requires a shift to one of the other actions at about 82 years. The scorecard shows implications. Colours relate to actions A (red), B (orange), C (green), and D (blue). (Source [11])

incorporate uncertainty about future conditions into their plans.[12]

However, developing adaptation pathways is not straightforward. The many practical challenges include the determination of tipping points (when conditions require an alternative strategy) and quantifying the added value of flexibility (detailed options analysis was considered too complex in a lot of cases). There was also the need to connect with the investment agendas of other organisations and to unravel the interdependence of measures in different policy fields and areas.

And the pathways may themselves need to flex and adapt to new knowledge or conditions. Timelines can be a particular issue due to the trade-offs between long lead times (certainty) around infrastructure developments and the nimbleness (flexibility) needed if the pace of climate change or other societal developments create issues sooner than originally anticipated.

Systematic monitoring and feedback

The Delta Programme has structured feedback mechanisms (monitoring, analysing, acting). These assess progress on the implementation of infrastructure projects, the performance of existing defences (through physical monitoring and review), and external developments that may require adjustment of choices, strategies and plans (such as responding to cyber risks). Collecting and integrating that feedback into decision-making is a central principle of Adaptive Delta Management.

As part of its feedback processes, the Delta Programme created a multi-disciplinary Signal Group that brings together authoritative knowledge institutes in the field of water, spatial planning and climate. Inputs are themed around ‘knowledge and innovation’, ‘climatic and socio-economic developments’ and ‘changes in societal preferences’. The resulting advice targets action at the appropriate level, including when to trigger decisions set out in adaptation pathways[12]. The inputs are also used to inform the six yearly review that revisits the Delta decisions and plans.

Stakeholder engagement

The Dutch ‘polder model’ (consensus-based decision-making) is said to have its origins in the need for communities to collaborate and cooperate on water management. Without agreement on shared responsibility for maintenance of the dykes and pumping stations, everyone could suffer.

Sustaining this collaborative ethos is a key part of the Delta Commissioner’s remit. Government (at national and local levels), the business community, knowledge institutes and NGOs are involved through varied mechanisms. These include gathering independent advice from the Dutch Government’s Physical Environment Consultative Council (*Overlegorgaan Fysieke Leefomgeving*)[13], and hosting an annual Delta Congress to connect stakeholders and stimulate knowledge sharing. One important outcome from these activities is to secure on-going confidence in the governance system and political commitment as the Delta Programme evolves.

Efforts are also made to involve citizens, including through local engagement on projects affecting them directly. There is variable take-up or impact. While public confidence in the effectiveness of flood prevention measures is a strong positive, it can undermine emergency preparedness. This 'levee paradox' (in which individuals have such high trust in the systems protecting them that they leave themselves unprepared) presents an on-going challenge for the Delta Programme.

Delta Programme: looking to the future

The recent six yearly review of the Delta Programme[14] reaffirmed its overall direction, with some fine tuning of programmes to reflect changing contexts. It highlighted the continuing importance of collaborative approaches, of making best use of available knowledge and of adaptive strategies.

The review also recommended:

- Additional focus on implementation (in order to achieve 2050 goals) and on raising awareness of the increasing risks from sea level rises beyond 2050. Recent severe droughts in the Netherlands have raised questions about pace: are the 30-year timelines envisaged for infrastructure works too relaxed given the increasing visibility of climate change impacts?
- Taking stock of experience to date with the adaptive planning tools and associated monitoring, analysis and action frameworks. While evolutionary infrastructure investments to date have been effective in securing progress and outputs are clear to see, measuring outcomes is a challenge: given the extent of climate change uncertainties, how do you assess the capacity of the system as a whole to adjust to climate impacts and, hence, whether pace is sufficient?
- Improving interconnections between the three core tasks of flood protection, freshwater supply and spatial planning, as well as reinforcing links to other societal / national initiatives: how might decisions in other related infrastructure systems (such as inland shipping) help mitigate risks or enable even more transformative options for tackling water related issues?

Section 3: Discussion and transferable learnings

Adaptive models are used in both regulatory and governance systems as a way of dealing with the deep uncertainties of complex systems or innovations. This case study focuses on how experience from Adaptive Delta Management might inform the design and application of such systems.

Adaptive regulation

Adaptive regulation takes many different forms[15]. In essence, it is defined as a regulatory framework that is explicitly designed to allow for changes in regulatory policies or rules over time as new evidence and knowledge emerges. The precise way in which this is achieved varies.

Planned Adaptive Regulation (PAR)[16] is characterised by the use of pre-defined mechanisms for adapting regulatory policies or designs towards an agreed end goal as knowledge is gained and/ or regulatory contexts evolve. As well as being forward looking (anticipating possible or desired futures), PAR requires a conscious plan and systematic effort to collect and review relevant performance indicators from the outset.

Box 2 provides examples of PAR. These span different sectors, nations and cultures to demonstrate that adaptive methods can be successfully applied in many different contexts. The examples include 'Agile Regulation' – an emerging concept that is broadly comparable[17].

Box 2: Examples of planned adaptive regulation

Retrospective reviews some time after implementation, which may be one-off or periodic, for example as seen in the periodic re-assessment of EU and US particulate matter standards (air quality) supported by investment in the accompanying science to advance knowledge.[16]

Goal based regulations that specify overall regulatory outcome but allow for evolution, informed by practical experience, in how to achieve this. In Rwanda, such approaches enabled novel uses for drones (delivery of medical products, agriculture and infrastructure inspection).[18]

Regulatory sandbox in which existing regulations are relaxed within a controlled and monitored environment to trial innovations. In Singapore, temporary relaxation of environmental regulations enabled pilot tests on a novel on-site compact waste gasification plant.[19]

Phased, conditional approvals for medicines by the European Medicine Agency, with clinical trials supported by real life data, being piloted to allow for early and progressive patient access to a medicine in areas of high medical need.[20]

Adaptation within governance systems (beyond state led regulation), such as the transnational regime managing Internet protocol (IP) address delegation.[21]

Adaptive methods work well in some environments but may be unsuitable for others, making it important to understand their strengths and limitations. For example, the benefits of a stable regulatory system may outweigh the value of adaptive models.

The following sections outline conditions that can support or hinder adaptive regulatory methods and relate this to the Delta Programme experience (which has many parallels). Detail on the regulatory aspects is provided in the International Risk Governance Council's conference report on PAR (2016)[22] and a foresight review on the future of regulatory systems (2021)[23].

Success factors

Adaptive regulatory designs benefit from the following:

- The end goal needs clear definition ('adapt to what, exactly'?), consensus on the use of adaptive approaches and firm commitment to the practical implications (such as secured funding to support the underpinning research and systematic data collection). This can be challenging given the power dynamics often involved in regulatory developments.

  The national imperative to address flood risk and secure freshwater supplies, underpinned by a strong political consensus, has helped the Delta Programme. While the long history of collaboration on water management in the Netherlands (the so-called 'polder culture') is a helpful enabler, the governance mechanisms supporting adaptive methods go much wider.

- Systems thinking brings helpful discipline and structure to understanding the dynamic issues at play. A whole-of-system view is particularly important given the interconnections between different parts of government, organisations and people involved and the external factors that disrupt (or become disrupted by) how the overall system behaves. In regulatory contexts, taking a systems approach also opens different options for achieving the overall outcomes.

  Although the Delta Programme took a systems view from the outset, the latest review[12] highlights that even more is needed to deal with the interdependencies between flood protection, freshwater supply and spatial planning as well as wider government initiatives.

- Trust is fundamental: there needs to be stakeholder confidence (i) that there is genuine long- term commitment (ii) that decisions will not get retrospectively reversed too easily downstream and (iii) that people anticipating future revisions will not undermine compliance. Trust can be supported by 'policy commitment devices'[24] (such as new institutions, legislation, secured budgets for knowledge or capability development, or financial incentives).

  The Delta Act addresses this aspect with its creation of an independent Commissioner, secured long term funding and emphasis on collaboration and cooperation.

- Adaptive leadership: in which there is an explicit acknowledgement of uncertainty and anticipation of how issues might develop (through tools such as scenarios or horizon scanning). It makes use of structured mechanisms to identify and systematically track key indicators (early warning systems). The resulting feedback is integrated into decision processes and enables adaptive regulatory responses. 'Adaptation pathways'[25] offer one way of mapping out policy options and visualising options.

  The adaptation pathways used by the Delta Programme proved effective in raising awareness of uncertainties and communicating how futures may play out. But there are still challenges in turning what might be seen as hypothetical options into timely action when change is needed.

- Diversity: the ability to draw on diverse perspectives is of critical importance when tackling complex systemic issues. This diversity can be further enhanced (and trust built) by engaging interested individuals from outside established institutions, such as the intended beneficiaries of the regulatory policies, who may not have what is seen as the 'usual' professional or academic background. Getting full value from these inputs often needs specific tools (deliberative mechanisms) that can help ensure common language and shared understanding, and hence support effective dialogue and debate.

  The Delta Programme goes part way towards this through the independent inputs of the Physical Environment Consultative Council and its Delta Congress, although these are largely targeted at a professional community who share a common language and interests.

Potential limitations

Regulatory designs are highly context specific. Adaptive approaches will not always be appropriate. Potential limitations to their application include:

- It may be a step too far. Adaptive regulation does not sit well with the 'regulate and forget' mind-sets seen in many jurisdictions and the cultural shifts involved may be demanding. Similarly, recognised regulatory vulnerabilities such as trans-boundary issues, knowledge asymmetries or power imbalances can all feature even more strongly in disruptive environments. They could act as barriers to new, more adaptive, methods. (**Figure 5**).
- Implementation costs (both financial and time) may prove to be prohibitive given the potential

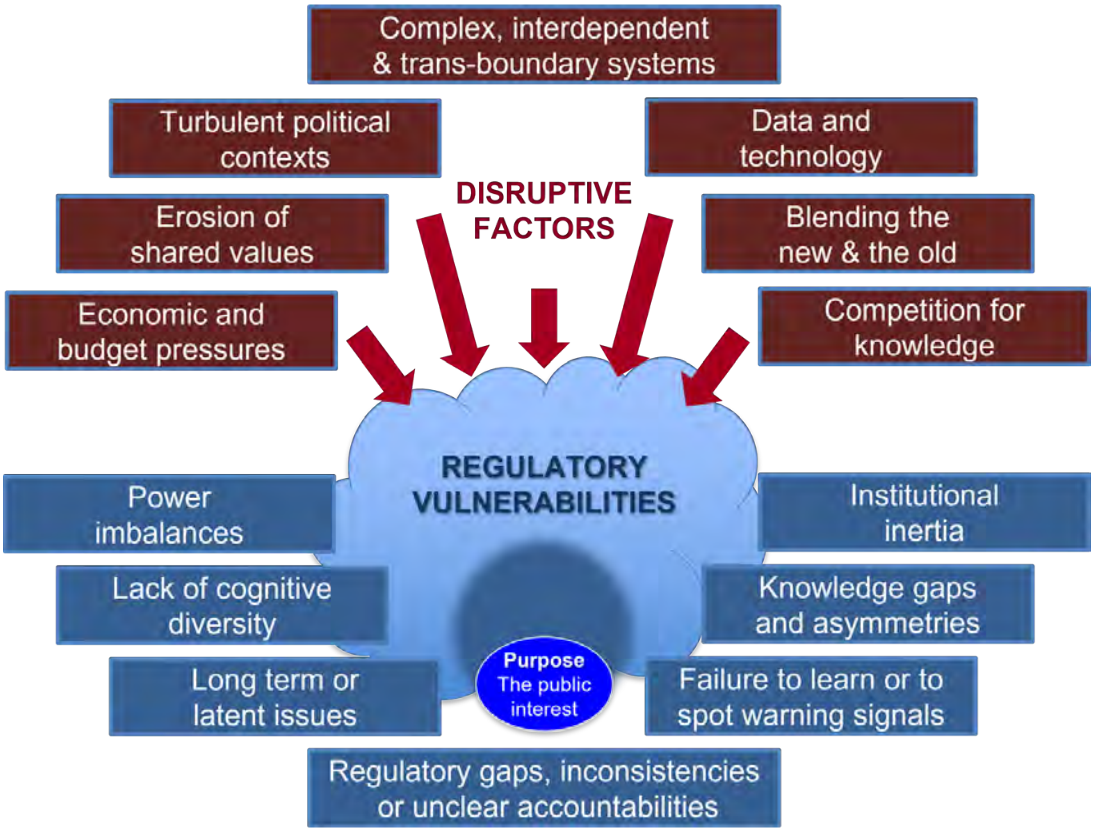

Figure 5: Vulnerabilities of regulatory systems (Source [23])

demands of both data collection and analytical capabilities. While the fundamental importance of water management to the Netherlands warrants high levels of investment in knowledge development and critical infrastructures, the timelines and amounts involved have been significant. In other domains and applications, the question about how much complexity is warranted and identifying what is 'fit for purpose' may feature even more strongly.

- Citizen attitudes. Although engagement can help sustain public trust and create the conditions needed for adaptive methods[26], there are limits: under what conditions and for what purposes will society accept experimentation and adaptation? Participation might also be less effective than imagined: a review of Dutch public consultation on water framework directives highlighted: relatively low citizen interest until they are personally affected; a sense that opinions shared had limited influence in shaping policy outcomes; and the questionable value of an open public participation process for highly technological policies. Care is needed about how citizen participation is used and tuned to the different stages of policy development.
- Practical issues, such as how to ensure timely detection of those tipping points that trigger a switch in strategies within situations that have large natural variability; and responses that may have significant lead times. There are also basic trade-offs to resolve within adaptive designs. Examples include: frequency of review (more rapid updating of policies vs. greater instability for those affected); scope of impact assessments (light touch vs. more comprehensive, but at greater cost); and the nature of decision mechanisms (rapid, reliable, automatic vs. slower, deliberative, discretionary).

Conclusion

There are compelling arguments for using planned adaptive regulatory methods – particularly for rapidly advancing technologies and for responding to an increasingly disruptive world. However, experience has shown that moving from a compelling concept to practical reality brings many implementation challenges, not least of which is tackling entrenched mind-sets and culture.

The continuing evolution of the Delta Programme shows what can be achieved. Progress to date highlights the value of its whole-of-system perspectives; its collaborative methods that draw in diverse stakeholders and enable knowledge sharing; and of the strong political commitments (with secured funding) that underpin its adaptive approaches and long-term focus.

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A comparative study of fire risk emergence in informal settlements in Dhaka and Cape Town

By Danielle Antonellis, Laura Hirst, John Twigg, Sandra Vaiciulyte, Reasat Faisal, Melissa Spiegel, George Faller, Richard Walls, Natalia Flores, Birgitte Messerschmidt

Executive summary: Catastrophic fires are frequent in informal settlements around the world, where one billion people live. A complex adaptive systems framework is developed to untangle the emergence and manifestation of fire risk. Insights from case study analysis in Dhaka, Bangladesh and Cape Town, South Africa reveal the importance of interdisciplinarity, broad participation, and systems mapping when addressing safety of complex systems.

Tags: urban fire risk, conflagration, informal economy, housing, inequality, complex adaptive system, pressure and release framework, Bangladesh, Asia, South Africa

Section 1: Background and introduction

Fires are a frequent, everyday occurrence in informal settlements in cities around the world. Their consequences can be catastrophic and include fatalities, long term injuries and emotional trauma, destroyed homes and assets, disrupted education and livelihoods. With a quarter of the world's urban population (around one billion people) living in informal settlements, this risk is a problem that urgently needs addressing.

The study looks at fire risk in informal settlements in two cities: Dhaka, Bangladesh, and Cape Town, South Africa. In Cape Town, research focused on the settlement of Imizamo Yethu, which has suffered numerous fires since its establishment in 1991, but none as devastating as the 2017 fire that lasted thirteen hours, killing four people, destroying more than 2,000 homes, and making 9,700 people homeless. [1] Korail, Dhaka's largest informal settlement, has similarly been affected by fire – in March 2017 a fire destroyed 4,000 dwellings and displaced an estimated 20,000 people. [2]

Whilst large fires such as these make headlines, the reality is that both cities' fire problems are chronic and worsening. The City of Cape Town Fire and Rescue Service responds to informal settlement fires every day. It reported a 150% increase in the number of fires between 2003–2018, with 289 fatalities in 2018 and 2,014 in 2019. [3] These figures do not account for fires that may have been managed by residents and not reported to fire services. In Cape Town, the number of fire-related deaths is known to be underestimated: the fire services only report deaths that occur at the scene of the fire incident, and not people who die from fire injuries later in hospitals. In Bangladesh, the number of fires has tripled over the past 22 years, but there is under-reporting of data on informal settlement fires. Bangladesh Fire Service and Civil Defense (BFSCD) data suggests there were fewer than 260 informal settlement fires per annum between 2015 and 2020 [4], however comparison between South Africa and Bangladesh in terms of number of fire incidents and casualties in respective informal settlements suggests the BFSCD data grossly underestimates these values.


Photo Credit: Justin Sullivan

In addition to a paucity of reliable data on fire incidences, there is little quantification of their consequences. There has also been a lack of attention to fire's causal factors: looking beyond how fires are ignited and spread via proximal housing conditions and energy practices, to the broader root causes and dynamic pressures that create these conditions. There is growing recognition that urban fires are not just technical and physical challenges to be managed at the site of ignition: they have complex social, political and economic dimensions. This study understands fire risk as generated by the interactions between fire hazard and the wider social, political and economic vulnerabilities experienced by those living in informal settlements.

This study explores and maps the complexities of these interactions. It asks how fire risk emerges and how fire safety is enacted in informal settlements. It provides information on systemic/root causes, impacts and how different groups of people respond to such fires. A number of key processes and interactions are highlighted that have previously not been taken into account by more traditional, engineered fire safety approaches that tend to focus on managing fire hazards rather than reducing fire risk holistically. This is valuable information that will help those working on urban fire risk reduction – such as fire safety engineering and humanitarian development practitioners, urban risk researchers, urban authorities, disaster responders and disaster management agencies – to contextualise knowledge beyond the technical and to identify key areas for future intervention.

Section 2: Analysis and insights

Fire risk in informal settlements emerges from processes of inequitable urbanisation, where fire hazards and multiple socio-economic vulnerabilities are created and reinforce each other. There is no one single root cause, but rather a complex entanglement of environmental and physical conditions and social processes and relations that interact to heighten fire risk. Structurally constrained conditions limit people's choice of where to live, and how, leading to ignition sources and conditions that give way to fire spread.

Pre-fire

To trace the development of fire risk in informal settlements, it is necessary to understand the contexts in which people and places become vulnerable to fire. **Figure 1** shows the architecture of a complex adaptive systems framework applied to fire risk, which integrates core tenets of the Pressure and Release and Complex Adaptive Systems models. [5] [6] This approach demonstrates how root causes and dynamic pressures lead to unsafe conditions, i.e., hazards and vulnerabilities that interact to produce fire risk. The accumulation of fire risk ultimately leads to fire incidents. Post- fire disaster consequences may generate further vulnerabilities through loss of assets, injuries, insecurity, reliance on riskier energy sources. These conditions can feed back to contribute to further fire risk emergence. This adapted framework is used throughout this study to untangle the emergence and manifestation of fire risk in informal settlements, and resulting fire consequences, in Dhaka and Cape Town.

Root causes of risk are found in the political, social and economic structures within a society that affect the allocation and distribution of resources, wealth and power among different groups of people. Here, it is necessary to acknowledge and understand the structures that have led to the widespread development of informal settlements in both cities. Dynamic pressures are more immediate processes and activities that translate the impacts of root causes, temporally and spatially, into unsafe conditions.

In South Africa, apartheid-era forced evictions and race-based town planning brought about spatial segregation. This removed individual land ownership rights for black South Africans and prevented black, mixed race, Indian and South Asian South Africans from living in centrally located urban areas. Black South Africans were forcibly displaced, and central locations reserved for white South Africans. Post- apartheid, a progressive legal and policy framework based on the right to housing, and a state-subsidised housing programme have tried to address some of these legacies. However, implementation issues, poor planning, and lack of coordination, capacity and political will have perpetuated an acute shortage of affordable housing available to low-income households.

This shortage of housing and associated municipal services has led to the ongoing growth and establishment of dense and poorly serviced informal settlements, largely on the outskirts of towns and cities, and disproportionately occupied by black South Africans. In post-apartheid South Africa, since 1996 (and especially since 2005) economic policy has shifted towards market liberalisation and economic growth at the expense of urban integration and greater equality. [7] Income inequality continues to follow racial lines, making formal housing inaccessible to large numbers of black citizens. The available peripheral locations provide fewer employment opportunities, creating poverty traps, and unsafe living conditions.

In Bangladesh, rapid urbanisation has primarily been driven by rural-urban migration. Push factors include climate change and associated risks which destroy village homes and livelihoods in disasters. Meanwhile, the country's rapid industrialisation as a ready-made garment exporter

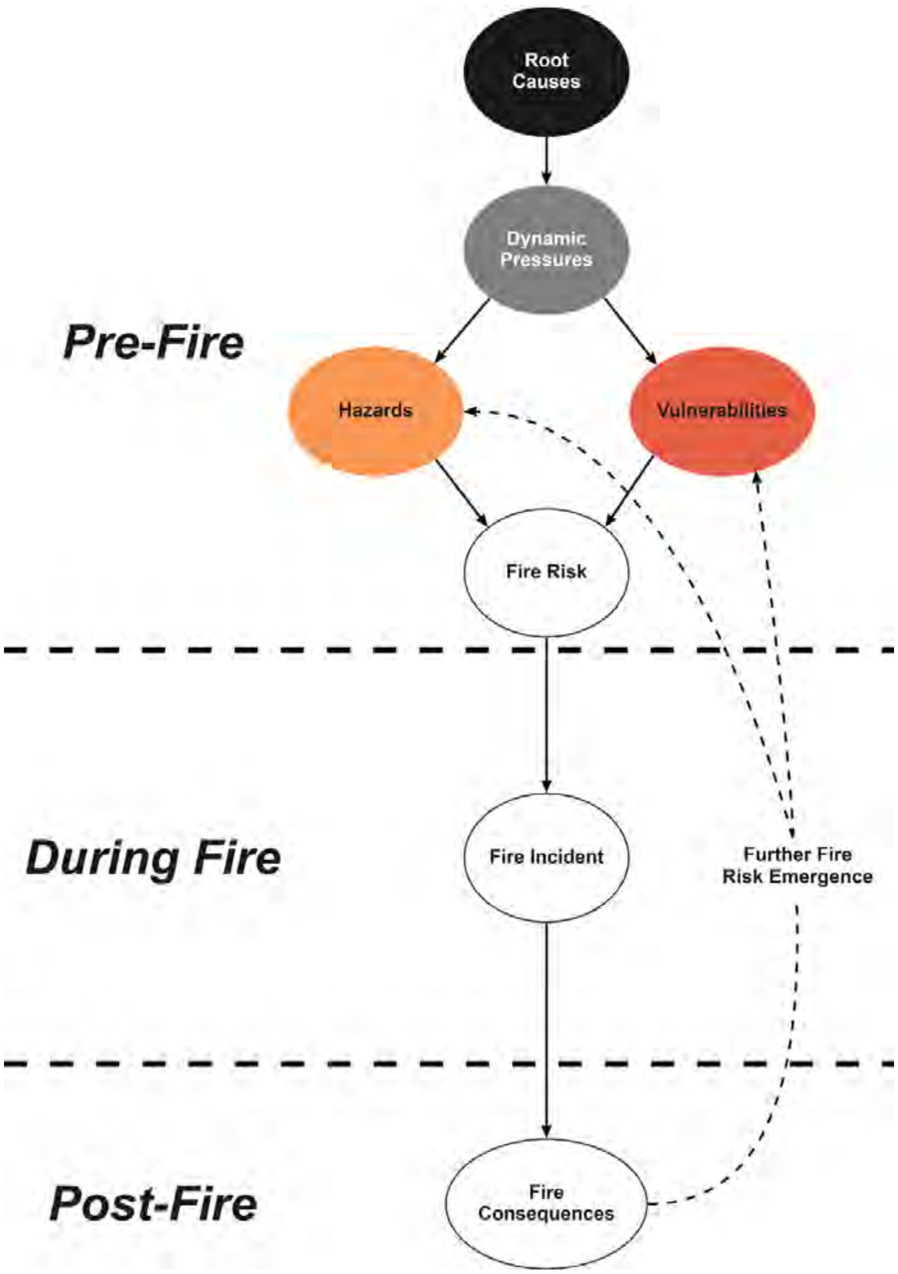

Figure 1: Fire risk complex adaptive systems framework

and associated employment opportunities has pulled people into cities. Urban densification and housing shortages have grown. Existing policies do not adequately address this rapid change, which is underpinned by weak governance, planning and urban management, inappropriate legal and regulatory frameworks, and lack of political will. Informal settlements are numerous, with their total population reaching 3.4 million in 2005. [8] Metropolitan regions have extended into formerly rural areas, resulting in dispersed and inadequate infrastructure planning and development. Urban development strategies and plans in Dhaka conceive informal settlements as illegal, contributing to ongoing marginalisation of residents in accessing adequate housing and infrastructure.

Historical legacies of urban planning, rapid urbanisation, and marketisation of urban development interact with contemporary conditions of poor governance, planning and urban management. This has led to the development of informal settlements characterised by unsafe conditions.

In general, informal settlements in both cities comprise low-quality housing with inadequate access to basic services and infrastructure. They tend to be unplanned and overcrowded, with very dense layouts. Land tenure status is often insecure, with households facing ongoing threats of eviction and demolition. Housing quality is largely dictated by affordability, resulting in the use of flammable materials. Residents may be discouraged from investing in safe materials due to tenure insecurity. Energy poverty, inadequate access to energy infrastructure and reliance on unsafe and potentially hazardous energy sources for cooking, heating, and lighting, significantly increases fire risks. Economic activities often take place within or adjacent to informal settlements, due to settlement in peripheral locations as well as socio-economic exclusion from formal employment opportunities resulting from social marginalisation. Ignition sources arise from these structurally constrained energy and livelihood options and spread via highly flammable housing materials, and dense housing layouts with small or non-existent separation distances.

In South Africa informal settlements are characterised by profound inequalities in access to basic services such as water, sanitation and electricity. Access to water is generally limited to communal water sources, with municipally supplied communal standpipes often located inconveniently at the perimeters of informal settlements. [9] Access to fire hydrants is limited. Formal electricity connections require the creation of micro grids or connection to the major grid system.

Roads may be unpaved and unnamed and houses unnumbered. Houses are constructed from affordable materials including corrugated iron, plastics, cardboard and timber. [9] In South Africa, municipal electricity connections are not allowed on private land, and informal settlements are often at a distance from networks. Informal settlement residents in Cape Town rely on a range of energy sources to meet their needs, including electricity, paraffin, candles, gas, wood, and coal, all posing ignition risks.

In Dhaka, informal settlements are often located on government-owned land, where eviction risks exist due to land ownership disputes and the market value of surrounding areas. Population density is high; informal settlements take up only 5.1% of the city's total land but 37.4% of the total city population. [10] Settlements are found in peripheral, suburban areas but also near city centres due to access to livelihood opportunities. [8] Houses are built using low-cost materials, including mud, bamboo, corrugated iron sheets and bricks. [8] Access to adequate water and sanitation is limited. Pathways are narrow, ranging between 60–90cm in places. In Dhaka, informal settlement households cannot legally connect to the formal electrical or gas networks, so informal connections and alternative energy sources such as firewood are the primary energy sources used. Ignition risks arise via the use of naked flames indoors or in close proximity to flammable materials, or from informal, unregulated electricity connections which are often established with naked wires and are prone to overloading, causing sparks.

A range of largely unregulated informal economy activities in both cities was documented, including small-scale manufacturing, food vending, salons and fuel sales. Ignition and spread risks arise from the ways in which these activities use flammable substances, contribute to fuel loading, and use open flames, gas and informal electricity connections. For example, a fire incident in 2016 in Korail, that destroyed 500 homes, ignited in the kitchen of a restaurant, and spread rapidly due to the fuel load of a neighbouring blanket and pillow shop. [11]

Arson is another known cause of fire ignition, allegedly used by landowners or interested parties to clear informal settlements for public or private development in Dhaka. Its incidence can be traced to market-driven urban land development and informal settlements' land tenure insecurity.

During a fire

When fires happen, residents are the first responders, and take actions such as raising the alarm, evacuating, moving possessions to safety, creating fire breaks, gathering water, and fighting fires. Inadequate firefighting equipment, training, and personal protective equipment limit the effectiveness of residents' responses, among other factors. City fire services in both cities often attend informal settlement fires but a lack of urban infrastructure such as road networks and water supplies in addition to wider issues of fire service resourcing and capacity can hinder efforts. The density of informal settlements not only contributes to fire spread but also prevents fire response vehicles and equipment from entering.

This lack of effective formal response leads to greater likelihood of fire spread and large conflagrations. In Dhaka, the average fire services response time was significantly higher in informal settlements, with an average of 68 minutes, compared to 28 minutes for the more formal residential areas in the city. [12]

Post-Fire Consequences

Property loss, fatalities and injuries are typically considered in studies of fire risk in informal settlements and tracked through fire incidence data collection systems. However, other direct and indirect consequences are rarely traced. Fire disasters can indirectly impact on livelihoods, education opportunities, and long-term mental health of residents. These shocks and stresses post-fire increase residents' socio-economic vulnerabilities in the long run, which feeds into a vicious cycle of hazard exposure and vulnerability, as well as cycles of poverty and exclusion.

Fire safety systems

Fire safety in informal settlement can be viewed as a hybrid system as opposed to a top-down command and control system. These hybrid systems comprise engineered fire safety subsystems extended from formal areas and ad hoc fire safety subsystems, which emerge and adapt to these contexts shaped by marginalisation and limited resources. There is no centralised authority – no clear stakeholder or group with designated responsibility for fire safety in informal settlements in Cape Town or Dhaka. Instead, the system constitutes self-organised actors who have various roles before, during, and after a fire, which may overlap or interact, but without much coordination. This lack of designated roles and responsibilities is reflected in the notable absence of urban fire safety from disaster risk reduction, urban resilience, and urban development discourses in both Cape Town and Dhaka. In this context, fire safety in informal settlements becomes even more of a neglected issue.

The current status of fire safety systems in Dhaka and Cape Town is characterised by a lack of oversight, governance, and communication and coordination between relevant actors, such as the fire services, disaster management agencies, urban development/planning agencies, NGOs and communities. When fire is addressed, it is through a narrow focus on physical fire hazards as opposed to a more holistic view of fire risk emergence and underlying root causes. Communities and residents are particularly excluded from city-level conversations about developing solutions, despite the central role they have in preparing, responding to and recovering from fire, and the disproportionate risk that they bear. This lack of effective governance has knock-on effects leading to ineffective responses and contributes to fire risk emergence. Fire risks manifest into actual disasters, and disaster consequences can make residents more vulnerable, producing more feedback loops of risk. Broader conversations around service delivery, in situ incremental upgrading and the reduction of structural constraints are needed, bringing in a wider range of city actors.

Section 3: Discussion and transferable learnings

This study set out to understand fire risk as emerging from complex urban systems. This approach is underpinned by an understanding of fire risk as arising from the interactions of man-made fire hazards and social vulnerabilities, which progress temporally and spatially. The research shows interactions between system components previously considered unrelated, or not taken into consideration by more traditional engineered approaches. The nature of fire risk within a complex adaptive system means that there is not a straightforward list of interventions that can be applied. To prevent fires in informal settlements requires systemic/structural changes in urban development, tenure security, housing and energy provision for low-income urban residents. These are long-term and enduring challenges. The key message is that making safer complex systems is a process of first understanding how and why people and places are made vulnerable and exposed to hazards via social, economic and political processes. Mapping out these risk emergence routes can help identify new knowledge and entry points for different (and new) stakeholders to understand the issues better and encourage better coordination efforts. For example, a basket of coordinated interventions is required (e.g., education, community response teams, early detection, capacitating fire departments), involving all active organisations within a community.

Recommendations for context-specific fire safety interventions (tactical and strategic) can be informed by this more realistic complex understanding of fire risk. Rather than emulating top-down command and control fire safety systems, institutionalisation of collaborative fire safety is needed that takes into account and supports the important role that all actors play [13]. This would help the whole system to bear accountability and responsibility, to counter the focus on 'responsibilisation'[1] of informal settlement residents for fire risk that emerges from across the city and not just at the point of ignition. Such an approach also takes into account the reality of informal settlement contexts for which formal command and control fire safety systems are inappropriate. The fundamental assumptions that underpin the success of formal fire safety systems do not apply in informal settlements (e.g., separation between buildings prevent fire spread, speedy response of fire services). The command-and-control approach minimises the role of the public in protecting themselves from fire (before, during and after an incident), which is not reflective of the reality, especially in informal settlements where residents are the only stakeholders able to respond quickly. [13] [14] There is, therefore, a need for more organised and supported community-based fire response.

A supporting and enabling approach recognises that communities and residents must be worked with to inform holistic fire safety solutions that navigate local barriers and leverage resources. Improved fire safety subsystems can be adapted; for example, fire services could adapt their policies, procedures, training and equipment to address the unique fire risk experienced in informal settlements, community-driven fire safety systems could be prioritized and resourced by municipal authorities and urban fora created for ongoing communication and coordination between stakeholders with the shared goal of improving safety outcomes. Resourcing is a key issue, particularly in the context of cities in low to middle income countries, however a step change in approach is urgently needed, which aims to avoid catastrophic losses.

Whilst this research has addressed city institutional responses and perspectives it is imperative to understand fire risk and fire safety practices from the perspective of communities and residents who live with high fire risk daily. Future research is urgently needed to document and share this knowledge and related adaptive practices. Helping communities to strengthen their capacities to protect themselves from fire and fostering an enabling environment that supports and encourages the emergence of local fire safety practices may be the most achievable and scalable way to improve fire safety and fire resilience in informal settlements. [15] Engagement with diverse stakeholders (governmental and non-governmental) is critical to develop an understanding of their role and location within the system, power relations between them, and the actual roles and responsibilities that they perform whether designated or not.
While there are opportunities to incrementally improve fire safety in informal settlements, through service delivery, in situ incremental upgrading, the removal/reduction of structural constraints, and where

appropriate engineering certain subsystems to be fit for purpose, it is critically important that the ad hoc nature of informal settlements is respected and that an enabling environment that promotes the emergence of fire safety is prioritized.

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Endnotes

1. "Responsibilization' refers to the process whereby subjects are rendered individually responsible for a task which previously would have been the duty of another – usually a state agency – or would not have been recognized as a responsibility at all." (Wakefield and Fleming, 2009)

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Community evacuation from wildfire events

By Dr Steve Gwynne, Dr Georgia Bateman, Dr Erica Kuligowski, Dr Max Kinateder, Afroza Mallick, Hannah Nevill, Dr Enrico Ronchi, Prof Guillermo Rein, Amanda Kimball

Executive summary: Wildfire evacuation events were examined to demonstrate their complexity. As part of the wider project, data from a US wildfire exercise was used to configure a macroscopic evacuation model – to simulate evacuation scenarios and capture some of the complexity present. To complement this, this case study explores complexity by identifying event dynamics and examining how they unfold to form a narrative – given events/evacuee decisions compiled from real-world incidents.

Tags: Fort McMurray, Roxborough Evacuation Exercise, pedestrian evacuation, traffic evacuation, community vulnerability, emergency planning, wildland urban interface, evacuation modelling, simulation, North America

Section 1: Background and introduction

According to the NFPA (National Fire Protection Association), a wildland fire is defined as an: 'unplanned and uncontrolled fire spreading through vegetative fuels, at times involving structures.' Where these begin to affect urban areas, these events are termed 'wildland urban interface' fires (WUI fires), as depicted in **Figure 1**. We tend to hear about these more – as they directly affect people, as depicted in **Figure 2**. Wildfires are an important safety issue in many regions of the world.

Such fires can threaten both rural and urban areas – affecting the short-term (life safety, infrastructure and the economy) and long-term (the environmental conditions, community health and well-being, tourism, etc,) status and viability of a community.

Wildfires increasing in frequency and severity

The frequency / disruption and severity / damage of wildfires affecting communities is increasing – for instance, the number of evacuations required because of a wildfire threatening a community. For example, as shown in **Figure 3**, those occurring in Western Canada and in California are of particular concern. Two examples demonstrate the complexity and cost of such events and the need for improved situational awareness and understanding of such events.

The Fort McMurray wildfire spanned 10 weeks in 2016, costing approximately US$10billion, producing disruption to local communities (an evacuation of 88k+ people) and industry (interruption to nearby tar sands refineries). The incident was marred by challenges in assessing the movement of the wildfire and its impact on evacuation routes – and on public communication efforts. As a result, command centres and refuges had to be repositioned during the response (given the unanticipated movement of the fire and evacuee response). The only deaths occurred during the evacuation itself.

More recently, Paradise (California) was subject to a catastrophic wildfire event (affecting a population of 26k). Paradise had an evacuation plan, with four evacuation routes for the population. Residents were familiar with these routes and preparatory exercises had previously been conducted. However, during the incident, two of the routes were blocked by the fire, requiring responders to focus their efforts on supporting the evacuation rather than addressing the incident. Delays in the evacuation meant residents were forced to take refuge in stores wetted by firefighters. Critical infrastructure (e.g., hospitals) were affected requiring ad hoc transportation plans. Personnel from surrounding areas were requisitioned to assist, having a knock-on impact on those areas. 85 people died. So what?

Properties of wildfire evacuation

A wildfire evacuation has several properties that add to its complexity:

- Involves multiple domains (e.g., a fire, land topography, infrastructure, human response, etc.).
- It is highly coupled (the fire can affect the roads available and the behaviour of the citizenry, which might affect the responders reaching the incident).

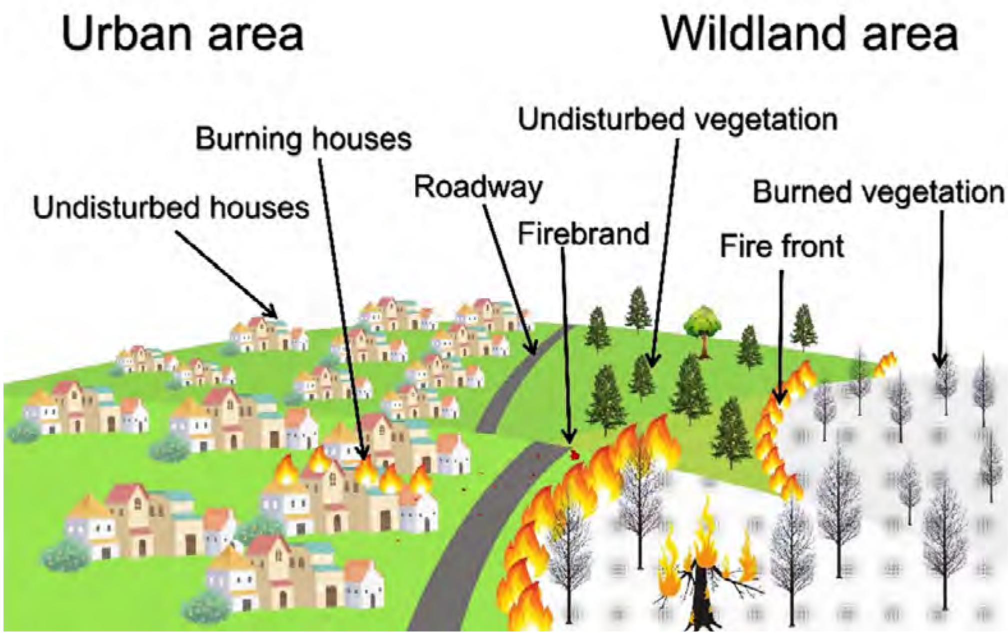


Figure 1: The interface between a wildfire and urban settlements, highlighting the ways in which the fire might affect the surrounding areas (courtesy of Dwi Purnomo).

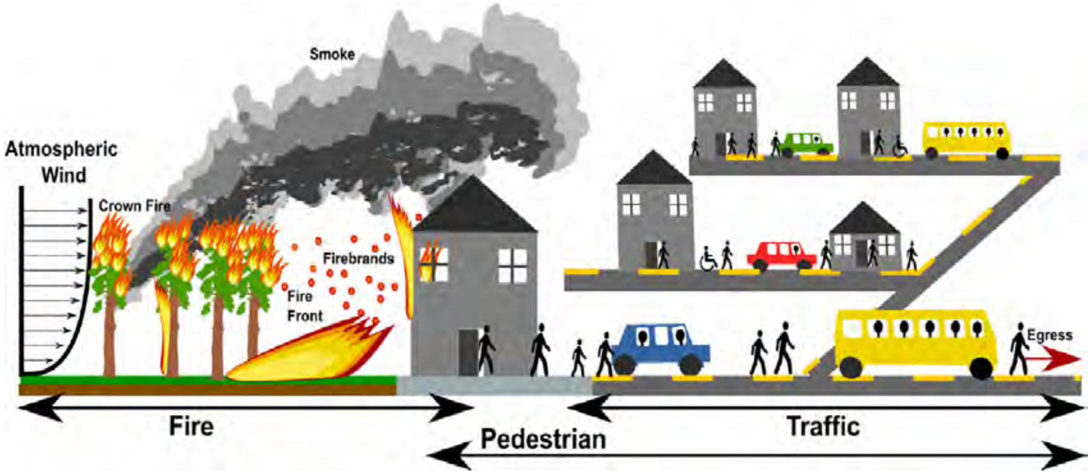


Figure 2: Fire, exacerbated by wind, impacting infrastructure and people (courtesy of Harry Mitchell).

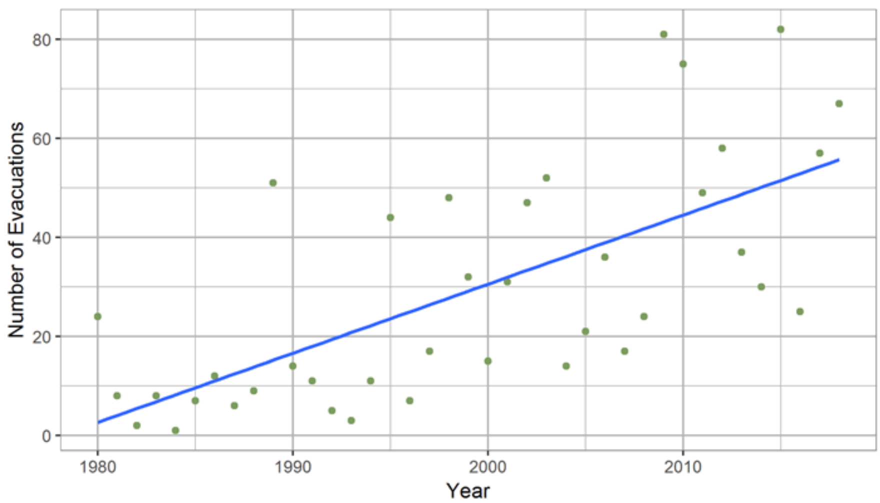


Figure 3: Example of Canadian evacuations (Source: Government of Canada, 2020).

- Involves large-scale (it may cover tens of square kilometres and reach communities hundreds of kilometres from the source).
- Involves multiple organisations / actors (individuals, businesses, communities and government agencies) over a long period of time.
- May involve many modes of movement, information sharing and intervention (e.g., access to social media, formal notification, individuals interacting).
- Potentially multiple incidents (a fire front can produce embers that then start secondary fires).

These actors/ factors interact, producing emergent conditions. These differ over time and the area affected. These affect the information available, perceived risk and actions performed by those involved.

It is possible to gain a clearer insight by accounting for these interactions and the aggregate outcomes – seeing the whole process as a complex system, as depicted in **Figure 4**.

When a fire develops, the location, severity and spread of this fire will be sensitive to the vegetation / fuel present, the topography, and the weather.

Planning and intervention efforts are employed. These affect the public activities prior to the incident, the emergency procedures and resources to intervene during the incident. The intervention performed will be sensitive to the situational awareness of emergency decision-makers, the resources available for this intervention, and the planning in place – along with the actions of the public.

The members of the public subjected to the incident and those sharing resources involved in the evacuation. The public's response will depend on the community size and demographics; the understanding of the existence, location and severity of the wildfire incident; and the resources available (social, physical, experiential, technological, etc.) to the community. This will influence the decision-making process and the action taken. This will be constrained by the available infrastructure, along with the social grouping within which a resident finds themselves.

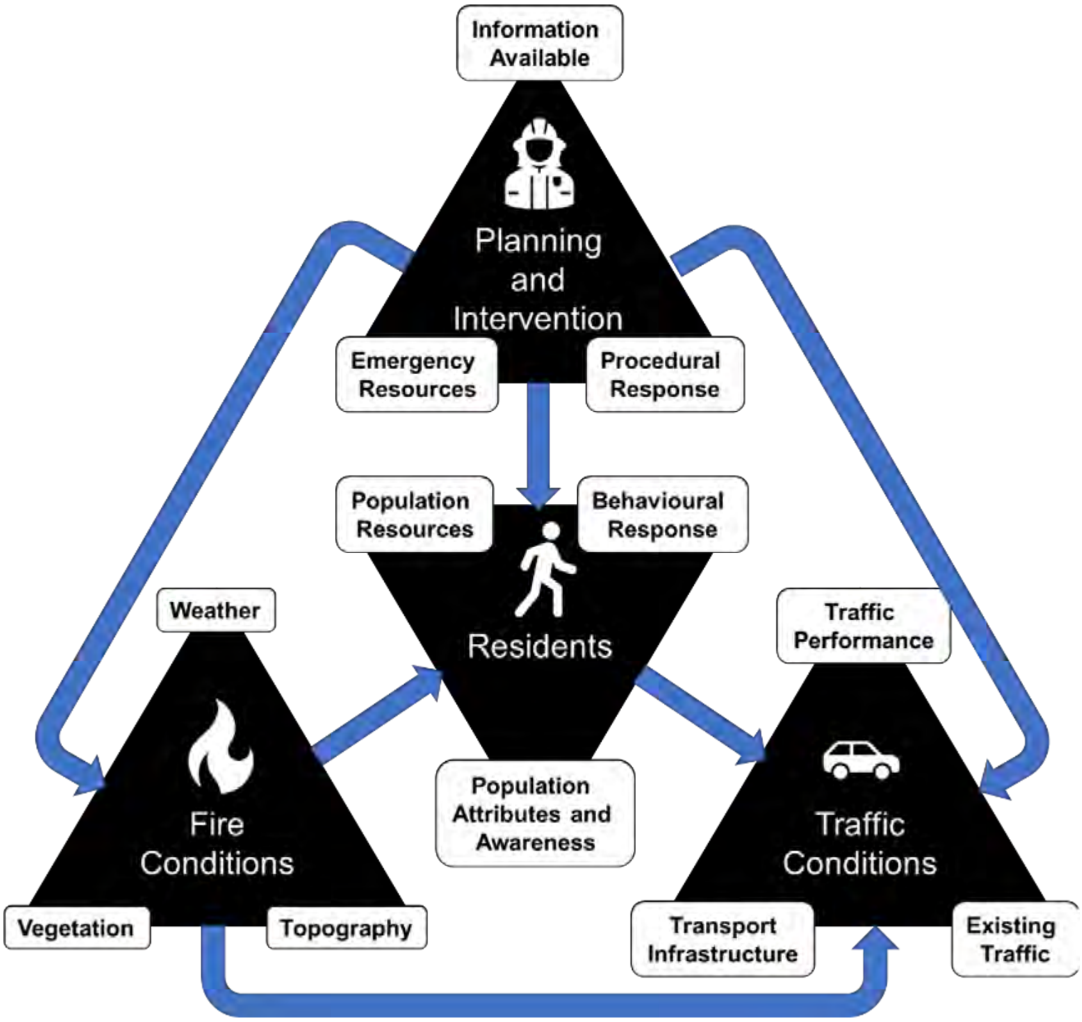


Figure 4: Some of the key properties of wildfire evacuation interacting as a complex system.

Community evacuation timeline

Initially, evacuation might involve pedestrian movement – walking to a local place of safety or moving to a vehicle. As such, one of the outcomes of the citizen movement might be an input into the traffic system and the local conditions produced within it.

The traffic conditions produced during the evacuation are initially influenced by the demand produced by the arriving evacuees into the system and the traffic already there, given the network capacity. The conditions will be shaped by the configuration and capacity of the traffic infrastructure in place, efforts to manage the movement of the traffic and the demand placed on the route capacity available.

These elements interact to produce conditions over the timeline of the incident. At the scenario level, the event can be viewed as unfolding across several distinct stages (see **Figure 5**). It is apparent that the coupling between the incident, the evacuating citizenry and attempts to manage and mitigate the incident are embedded within this timeline.

Evolving scales and conditions

The actions taken by the community and emergency responders during the wildfire will produce conditions that evolve – over space (e.g., kilometres) and time (e.g., weeks), as depicted in **Figure 6**.

The initial fire may develop spawning new fires remote from the original source through the transport of firebrands.

Fires may spread rapidly (faster than most people can run) with fire fronts extending kilometres in length. Smoke may affect communities located tens of kilometres away.

Similarly, multiple communities may be affected by a single fire and be subject to different information and guidance and may fall within different jurisdictions.

Therefore, both the fire conditions and the evacuation process will vary over space and time, be extremely dynamic in nature and be sensitive to changes in one of the influential domains (e.g., the land, the weather, the fire, emergency interventions, public actions, etc.).

This is starkly different from building fires (and associated planning)– where typically timescales are shorter, fires are localised, and the event occurs within one jurisdiction.

Why this matters

Given the above (and the results presented in the long version of this report) we make the following assertions:

- Wildfires pose a serious threat to community safety.
- This threat is expanding and increasing given environmental issues, as depicted in **Figure 7**.
- New communities are becoming vulnerable to this threat as it affects new locations.
- New communities are also becoming vulnerable to this threat as people choose to move to wildland urban interface locations.
- Communities historically threatened by wildfires are facing new and unfamiliar conditions – testing their understanding and resources.
- Given new locations and severity, wildfire conditions are diverging from the conditions faced in the recent past. This makes it harder to estimate the outcomes of new fires directly from historical fires.
- Wildfires are formed from various elements (social, physical and environmental) that interact in complex ways.

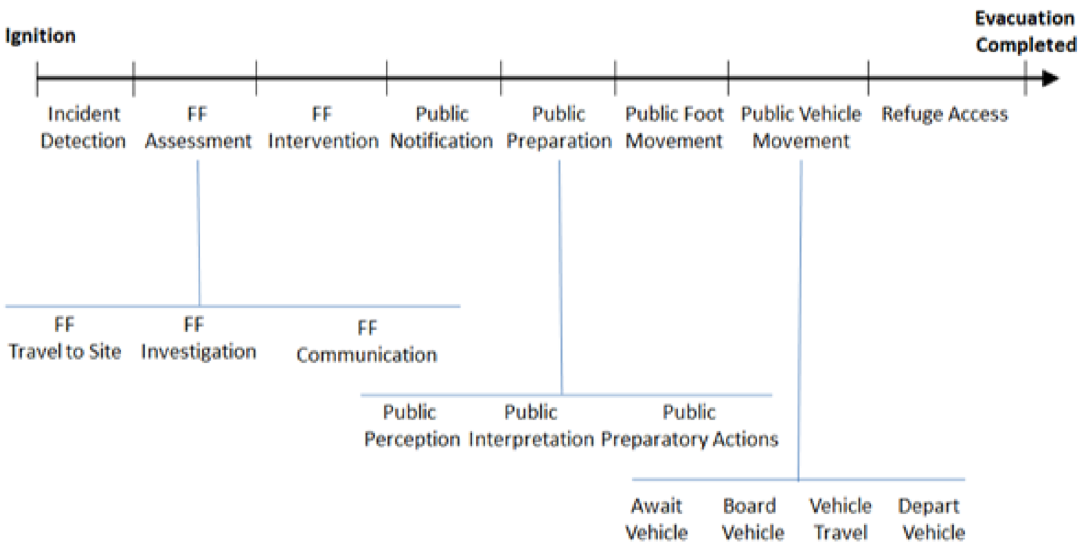


Figure 5: An example of a community evacuation timeline. FF=Fire-fighter(s). (Source: Initini et al (2020), Ronchi et al (2017), Wahlqvist et al (2020))

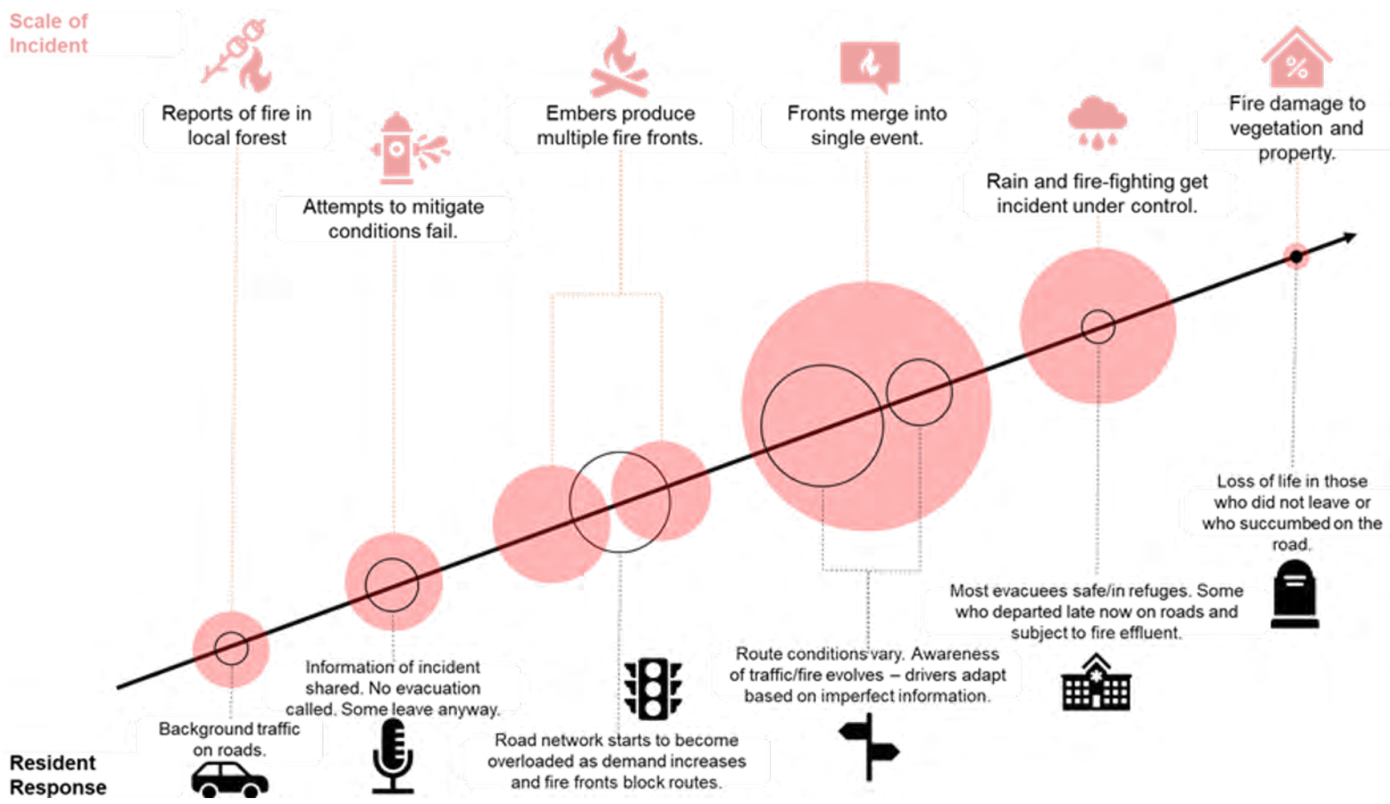


Figure 6: A depiction of the evolution, scale and condition of a wildfire evacuation given the fire conditions faced.

- To understand the threat posed, it is necessary to understand a community's capacity to cope with the conditions faced.
- New means to quantify community evacuation might be needed – to capture interactions between key elements and to cope with challenges in deriving projections from historical events.
- Modelling might assist in this endeavour.
- Such models would also be needed to support performance-based regulations or inform the development of prescriptive approaches.

Granularity of wildfire evacuation

Individuals affected by a wildfire may become aware of a wildfire through different means (e.g., official communications, direct exposure to fire cues, informal conversation with a neighbour, unreliable source on social media, etc.). Prior to this awareness they will have been involved in a range of routine activities.

These individuals will process this information and either individually or collectively determine when and how to respond. Assuming that they are in a household, the residents may discuss the situation, prepare and decide upon a response (i.e., whether they choose to evacuate and when they choose so to do). If they are part of a social group, then this response will likely involve assessing the capabilities of those with them (e.g., preparatory requirements, movement abilities, etc.).

They might eventually walk to their vehicle (or shared vehicle or public transport). Depending on their location, they may interact with other residents inside their building (e.g., in a multi-occupancy structure) with resultant congestion/interactions emerging in a staircase or interact when moving to shared parking areas. This admittedly seems like a trivial example here – not affecting overall performance. However, if this is transposed on to the evacuation of a 50-storey office block or a hospital then these interactions and resultant delays can become extremely serious indeed, as depicted in **Figure 8**.

Emergent conditions might arise from the pedestrian evacuation (e.g., queuing on stairs, boarding a public vehicle, etc.). Or, on the streetscape outside of their building, evacuees may encounter others moving to a local place of safety or to their vehicles.

If they are not at home (e.g., at work), then before evacuating residents may need to return home – potentially moving away from safety on foot or by vehicle. This has implications for traffic congestion, road management and on the delays incurred prior to their movement to a place of safety.

Assuming that evacuation to a remote location is necessary,

Figure 7: Wildfires reported in the media – 2017-2021. In areas where, historically, such events have been both expected (e.g., California) and unexpected (e.g., Sweden).

Figure 8: Example simulation (represented within the WUI-NITY model) of people evacuating downstairs and then transitioning from pedestrian to vehicle movement from a multi-occupancy location (Source: Ronchi et al (2017), Wahlqvist et al (2020)).

evacuees will likely board a vehicle and move off, joining the wider traffic system. If this involves public transport, then the capacity of the vehicle might limit the individual's/group's ability to board and move off – forcing them to wait for the next available berth.

The vehicle will eventually be the basic 'unit' of evacuation – possibly hosting several individuals – that then becomes the locus of their agency (their response). The entry of this vehicle into the traffic system is effectively the connection between the pedestrian evacuation and the traffic evacuation. As such, the resident's initial decision-making, preparation and movement to the vehicle might generate local emergent conditions of interest; these in turn provide input into the higher-level traffic evacuation. As such, a wildfire evacuation might reasonably be depicted as a system of multi-layered complexity, as in **Figure 9**.

Agency operates at multiple levels within the wildfire evacuation 'system': individual, residence, street, community, local, regional, national and international, etc. These may all affect the conditions produced and the eventual outcome (both local and general).

Several of these levels might be active at the same time – given different capabilities, objectives and opportunities.

The mode of this agency will change according to the conditions faced and the resources available.

This complicates the evacuation dynamics produced, but also increases the number of 'levers' available to influence the evacuation outcome. The management 'levers' might be available before or during the incident.

They might require different levels of resources, be available to different organisations and may be targeted at the levels of agency present (individuals, groups /

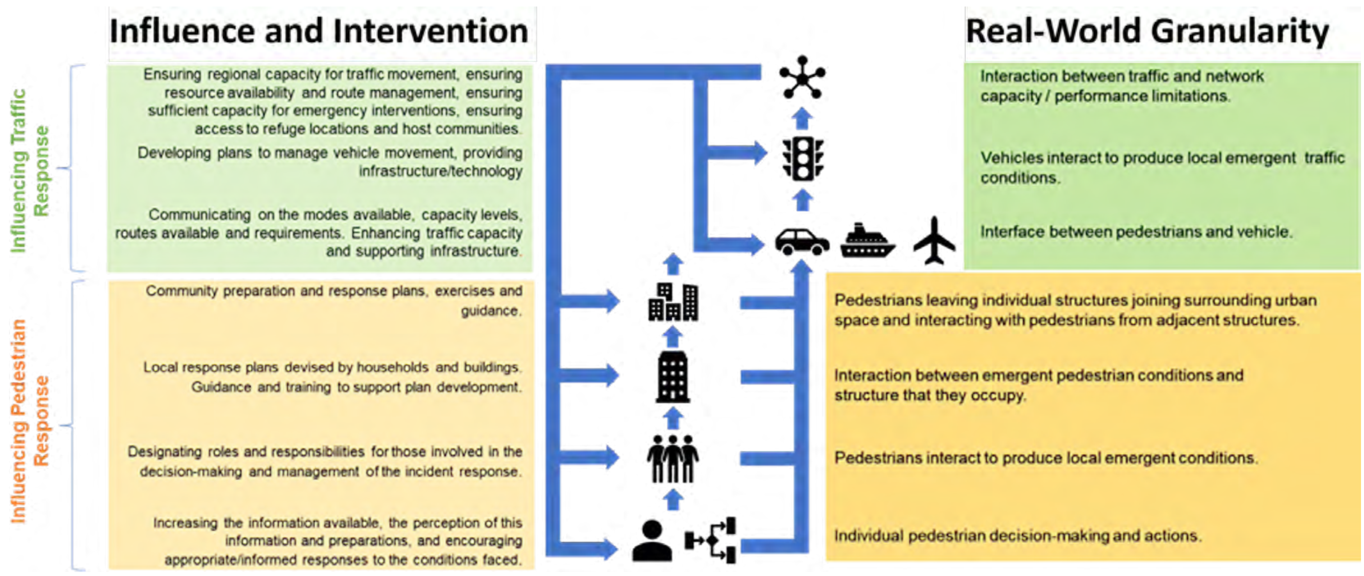


Figure 9: A wildfire evacuation as a system of multi-layered complexity.

vehicles, buildings, communities, regions, etc.). These might include education / outreach, regulation and guidance, emergency planning, exercises, incident notification, incident management, responder intervention, traffic management, etc. The complexity of a wildfire evacuation makes it sensitive to many different factors that operate at many scales. Their interaction can be outcomes out of proportion to the underlying change. Understanding this complexity allows for more interventions (at various levels and points in time); however, it also requires understanding the impact of these interventions as otherwise they can have unintended consequences that quickly get out of control or do not address underlying issues.

Section 2: Analysis and insights

Several cases were described in the long version of this study as the evacuation conditions were reasonably well documented, demonstrating at least some of the complexity described, and showed both that conditions evolve and that human performance can be a key aspect in this evolution.

The dynamics of a wildfire evacuation vary – depending on the scenario. The Fort McMurray wildfire evacuation is selected to demonstrate several aspects of wildfire evacuation and related community safety (with the attributes of complexity identified previously):

1. The evolving incident conditions (weather, fire development, remote fire locations, fire weather);
2. The response of the affected population (e.g., pedestrian movement, traffic movement), reflecting the diversity and vulnerability of the affected population and effectiveness of their decision-making (affected by information available);
3. Attempts at managing the outcome and the conditions faced (notifying people, fighting the fire, managing traffic, deciding to evacuate the community), given the organisations and groups present, emergency procedures employed at the local and regional levels and deployment of emergency resources;
4. Outcomes / consequences (loss of life, loss of property, loss of routes, traffic conditions, local/ national impact, etc.).

The following text is labelled with superscripts (in-line with the numbered list shown above, e.g. (1) reflects incident conditions, (2) reflects population response, etc.) to highlight where these factors are mentioned in the cited material. This is simply to demonstrate that the factors were at play, rather than assigning weight to the significance of their impact on the outcome.

Historical case study: Fort McMurray, Alberta, 2016

At 16:00 on 1 May 2016 a 0.02 km² wildfire was spotted in the Wood Buffalo area deep in a forest – 15-20km southwest of Fort McMurray (Alberta, Canada), depicted in **Figure 10**.[1]

Wood Buffalo has a population of more than 125,000 people including rural and urban communities. Of these, approximately 35% are temporary residents and 10% are First Nation communities; i.e., they have different levels of familiarity with the local area and different relationships with local authorities.

Strong winds (>70km/hr) and high temperatures (daily temperatures >30°C and humidity <12%) promoted the development of the fire.[1]

The immediate emergency response included water bombers being deployed, followed by

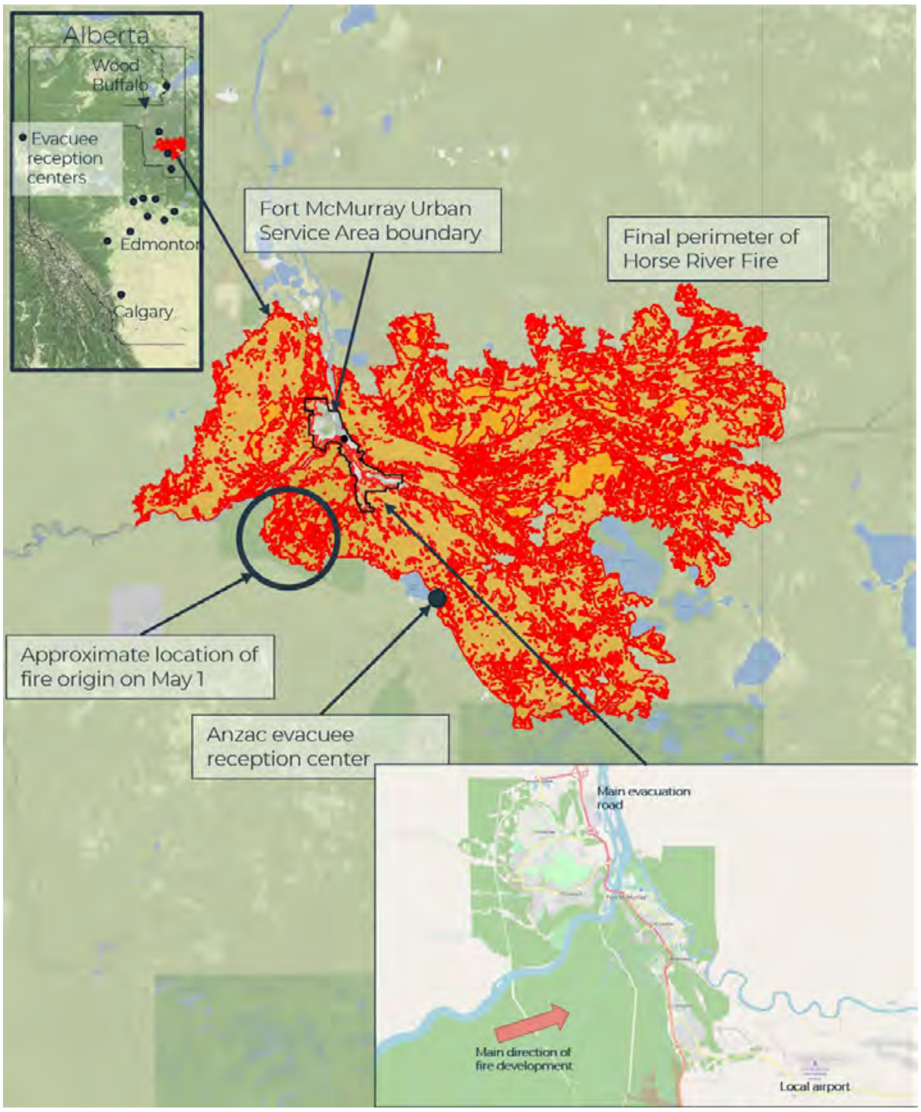


Figure 10: Fort McMurray (2016) case study. (Source: Alberta Agriculture and Forestry (2021), Institute for Catastrophic Loss Reduction (2019), OpenStreetMap (2021), Ronchi et al (2017)).

warnings issued to nearby campgrounds of the possibility of an upcoming evacuation.[2]

Within six hours of the fire initially being spotted, an evacuation centre was opened on MacDonald Island and a local state of emergency declared.[3] However, the next day warning levels were reduced[3] given that wind conditions improved and appeared to be blowing the fire away from the city.[1]

On 3 May conditions changed again and the fire entered Fort McMurray[1] leading to tens of thousands of people evacuating in short order to refuge centres in various locations.[2] Some of these evacuation centres were affected by changing fire conditions requiring them to eventually be evacuated themselves.[3]

During this (re)evacuation, two people were killed in a car accident (i.e., not directly by the fire itself).[4]

By the end of the day, more than 60,000 residents had evacuated, including all 105 patients at the Northern Lights Regional Health Centre.[4]

Highways were quickly overloaded with traffic.[4] To cope with this, convoys were formed.[2]

By 4 May, 1,600 structures had been destroyed with 100 km² of wildland involved.[4]

A provincial state of emergency was declared with 80,000 people instructed to leave.[3]

By 5 May, there were 49 separate fires burning and 1 4,000 people had to be airlifted from work camps north of Fort McMurray.[3]

Firestorm conditions were reported, and spot fires ignited new fires more than 1km away from the original source.[1]

On 6 May, 8,000 workers were evacuated from 19 oil sites as the fire spread north.[3]

Most people who fled the region did not have short-term contingency plans in place other than getting away from the immediate danger.[2] Local industry and residents, communities, post-secondary institutions and parks offered to host evacuees.[3] Reception centres were quickly put up across Alberta in numerous locations.[3]

On 6 May, the Alberta Premier announced emergency evacuation funds.[3]

The deployment and use of firefighting resources peaked on 3 June, with approximately 2,197 firefighters actively engaged.[3] The Government informed Albertans of the evolving situation with news conferences, information bulletins, social media, websites, call centres, emails, telephone town halls, etc.[3] Across the incident, more than 88,000 people were evacuated.[4] This primarily involved private vehicles, although public buses and aircraft were also involved.

Smoke generated by the fire affected the evacuee capacity to drive along the routes still available.[4] The incident lasted during May, June and July of 2016, affecting nearly 6,000km² of land.[4] Over 2,400 structures were destroyed in the fire, gas, electricity and water supplies were disrupted and the local airport closed.[4]

Management and evacuee decision-making were conducted continuously throughout the response, as depicted in **Figure 11**. These occurred at various organisational levels. There are numerous examples where these decisions (and outcomes) might have benefitted from more timely, accurate and complete information:

- Downgrading of 'evacuation status'
- Use of evacuation routes
- Allocation of evacuees to refuge camps
- Traffic management
- Refinery evacuation
- Community evacuation
- Re-entry management

This is not to criticise the response – only to suggest that during a wildfire event the decisions made are enormously sensitive to the information available and that the selection of a response might be sensitive to an estimation of the potential effectiveness of that response.

Hypothetical case (HC): Tale of the TAILs

A simple hypothetical example is now presented, across 12 inset tiles, to explore incident complexity. It is not based on any one case. Instead, the conditions faced, information available, actions performed, and the organisation responses are representative of those seen elsewhere in previous incidents. The intention is to capture a compilation of the factors and responses seen – but in one incident. This example is characterised by several timelines:

- Government: Those who regulate, guide and coordinate resources and actions beyond the site of the incident;
- Non-Government: Actors who are affected by the incident, but who have organisational responsibility in the private, non-profit, or commercial sectors;
- Emergency Response / Incident Management: Those intervening to affect the conditions produced by the wildfire incident or the incident itself;
- Incident: The evolving fire conditions;
- Population (traffic or on foot): The citizenry affected by the incident who might respond.

Each of the timelines hosts a number of 'episodes' representing key events. Episodes appear along each timeline. These reflect the changing conditions and their potential impact. Other actual incidents might also be similarly represented using this approach.

Actor response is described using up to three panes (see **Figure 12** for the generic format):

- Description. Overview of the situation described.

Figure 12: Three pane generic template describing actor response used in the 12 tiles depicting the Hypothetical Case Study.

- Graphic. A simple schematic of the conditions outlined.
- Status Pane. This includes a description of this population / person's Target (their objective at that point in time); Action (the behaviour exhibited to meet that target); Information (the situational awareness of those involved); and Location (the position of this population and the surrounding conditions).

This is included where decisions of interest are made. Elsewhere episodes are only described using Graphic and Description panes, to indicate condition changes.

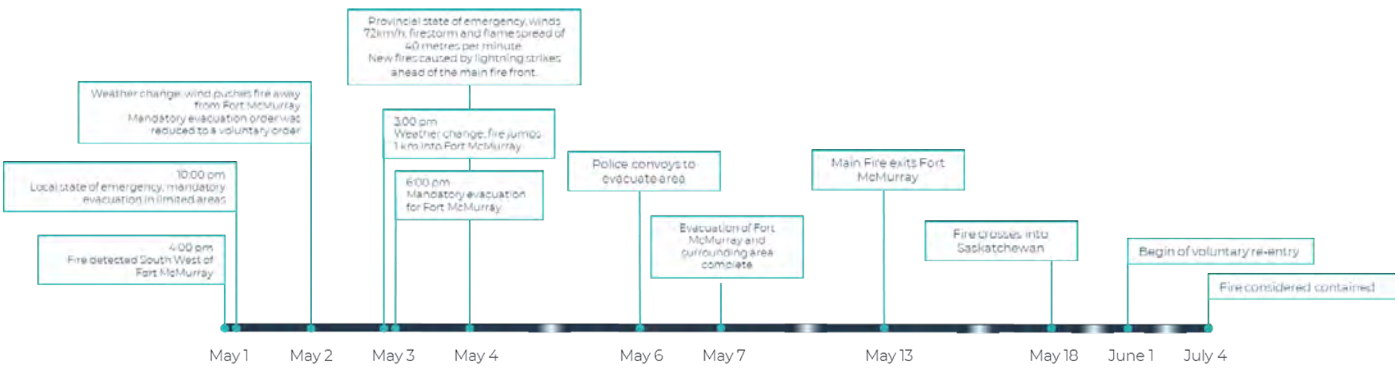
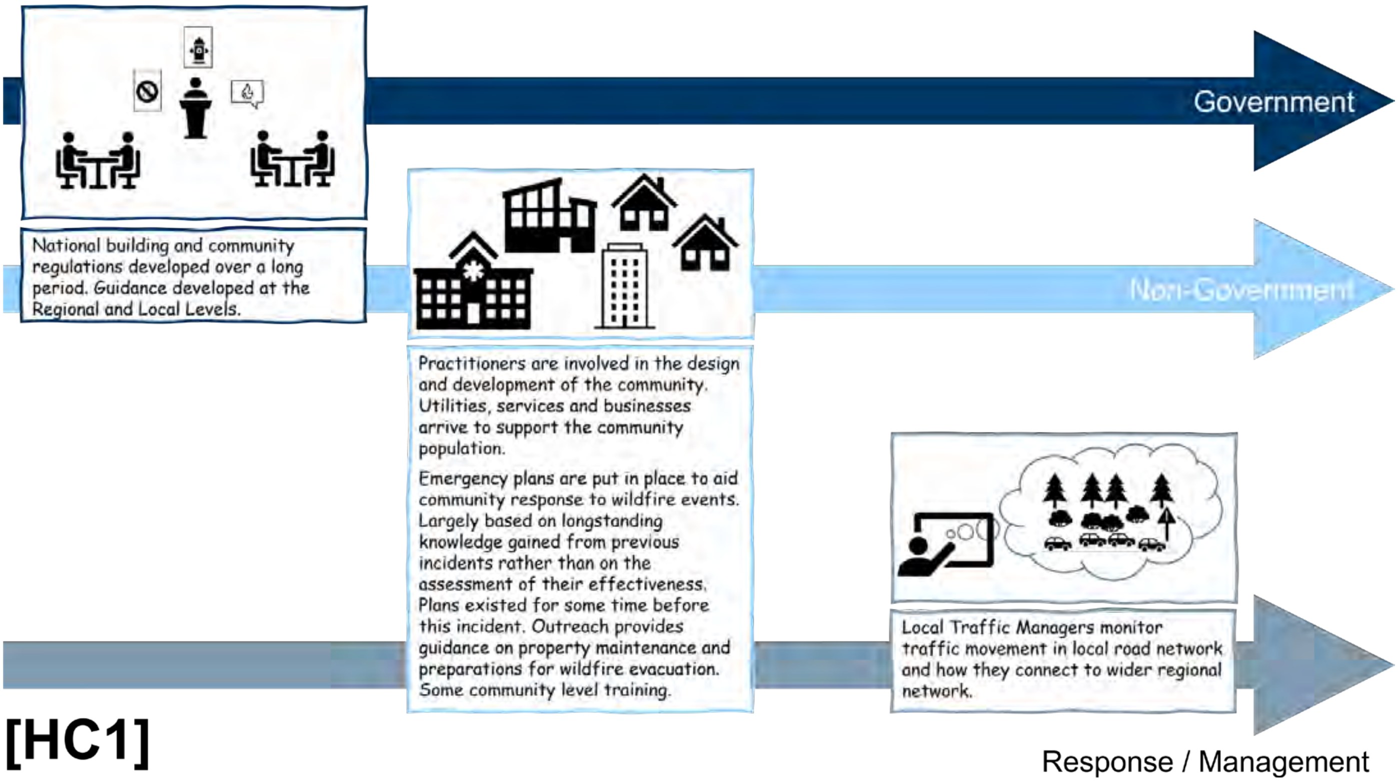
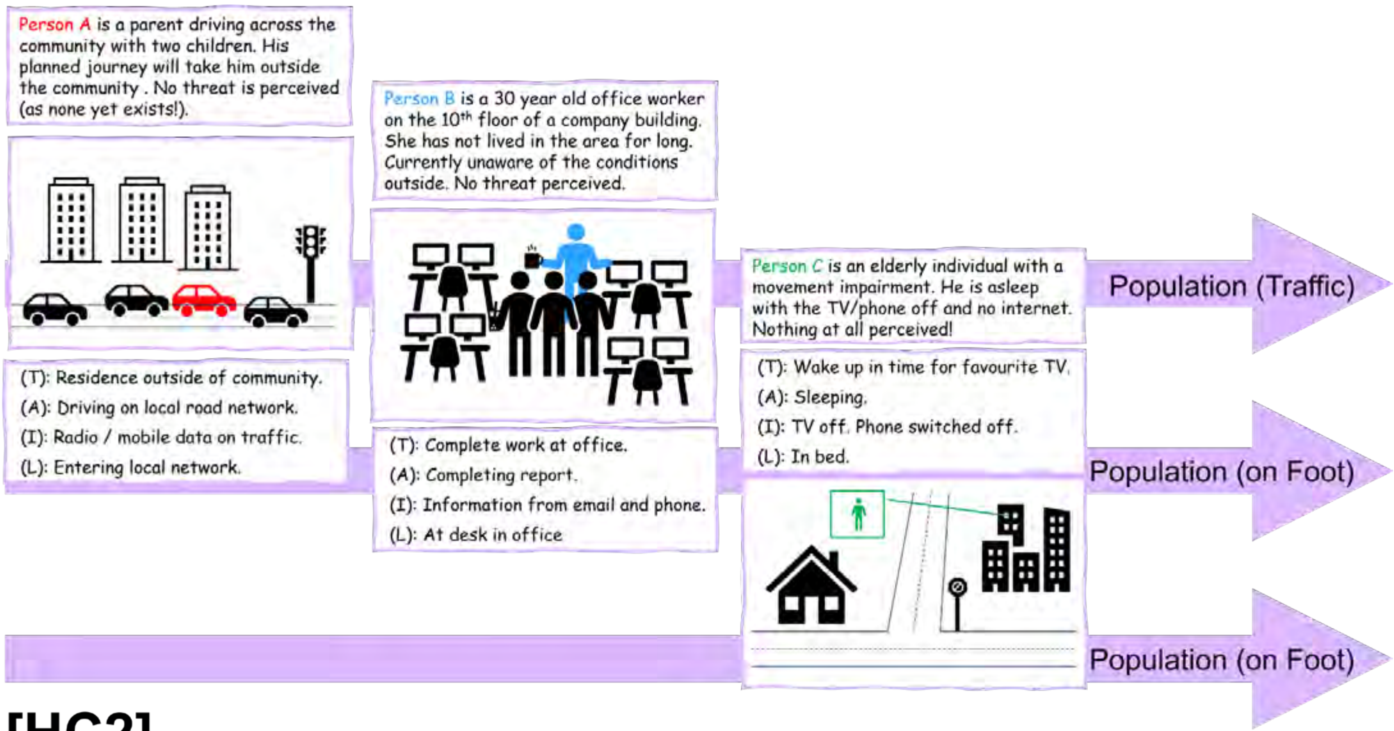


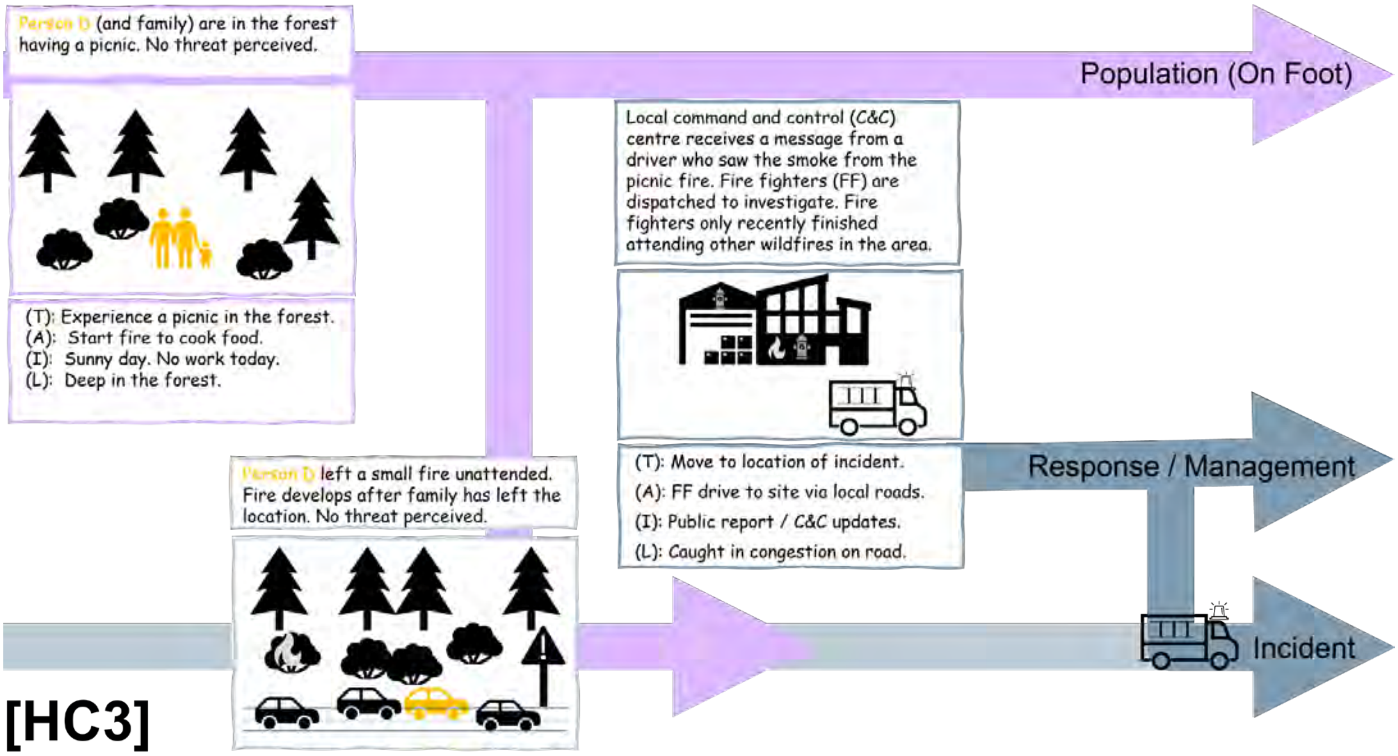
Figure 11: Management and evacuee decision-making timeline of the Fort McMurray (2016) case study.


Government
Non-Government
National building and community regulations developed over a long period. Guidance developed at the Regional and Local Levels.
Practitioners are involved in the design and development of the community. Utilities, services and businesses arrive to support the community population.
Emergency plans are put in place to aid community response to wildfire events. Largely based on longstanding knowledge gained from previous incidents rather than on the assessment of their effectiveness. Plans existed for some time before this incident. Outreach provides guidance on property maintenance and preparations for wildfire evacuation. Some community level training.
Local Traffic Managers monitor traffic movement in local road network and how they connect to wider regional network.
Response / Management

[HC1]

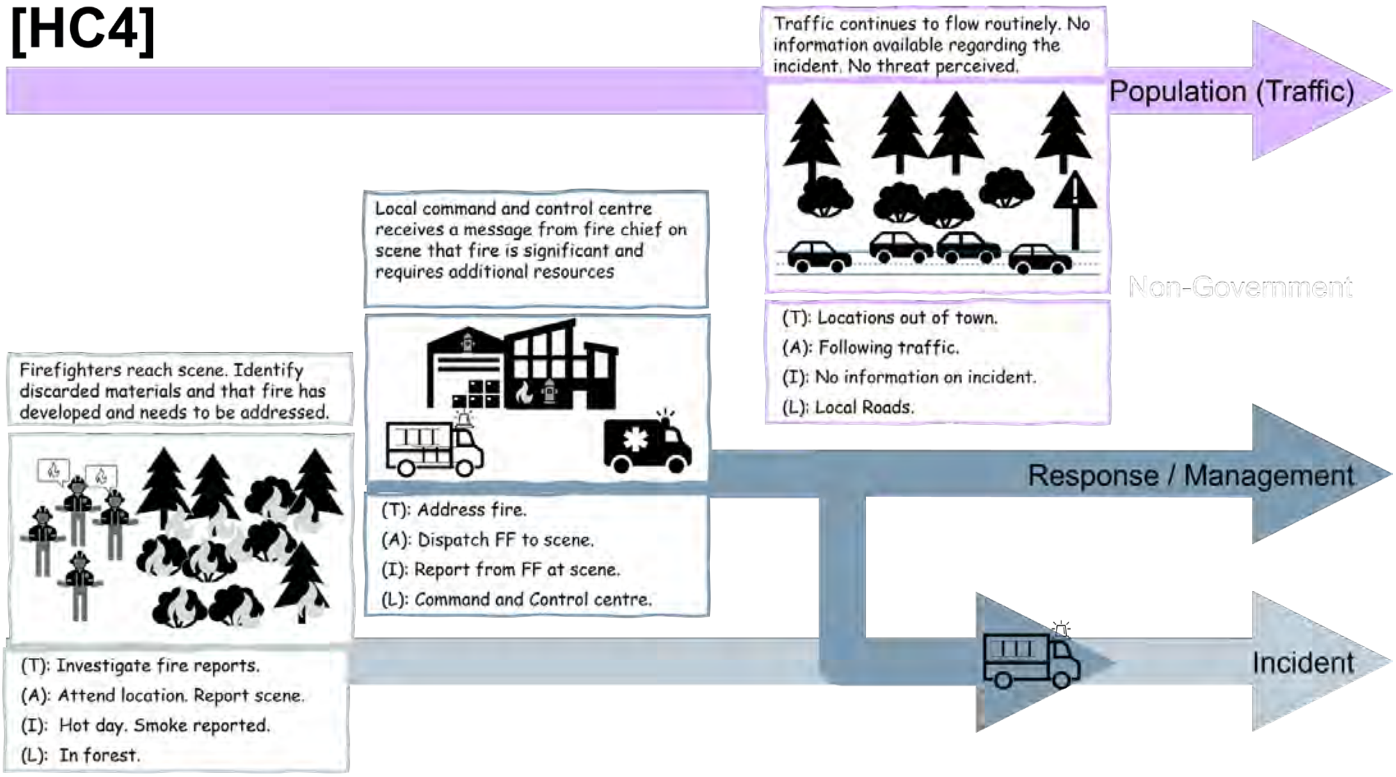

Person A is a parent driving across the community with two children. His planned journey will take him outside the community . No threat is perceived (as none yet exists!).
(T): Residence outside of community.
(A): Driving on local road network.
(I): Radio / mobile data on traffic.
(L): Entering local network.
Person B is a 30 year old office worker on the 10th floor of a company building. She has not lived in the area for long. Currently unaware of the conditions outside. No threat perceived.
(T): Complete work at office.
(A): Completing report.
(I): Information from email and phone.
(L): At desk in office
Person C is an elderly individual with a movement impairment. He is asleep with the TV/phone off and no internet. Nothing at all perceived!
(T): Wake up in time for favourite TV.
(A): Sleeping.
(I): TV off. Phone switched off.
(L): In bed.
Population (Traffic)
Population (on Foot)
Population (on Foot)

[HC2]

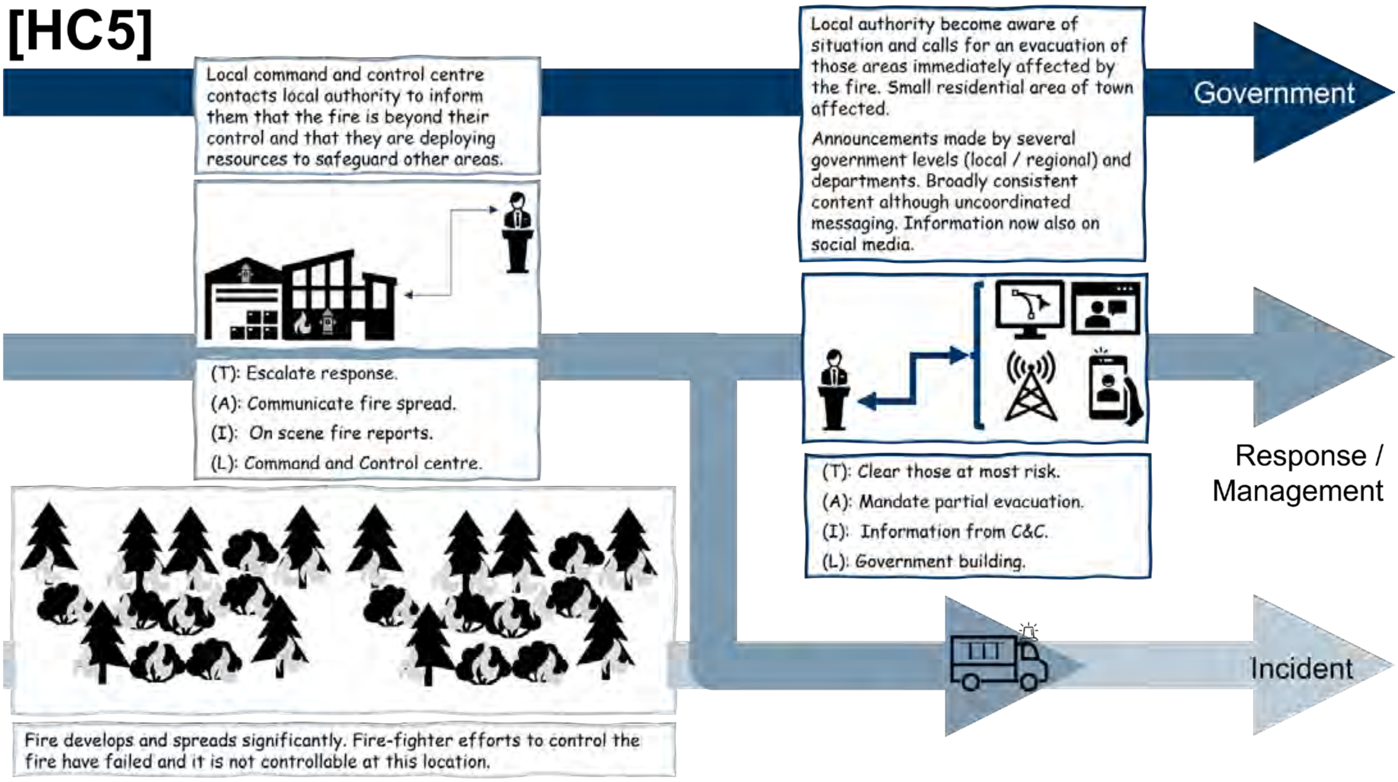

Person D (and family) are in the forest having a picnic. No threat perceived.
(T): Experience a picnic in the forest.
(A): Start fire to cook food.
(I): Sunny day. No work today.
(L): Deep in the forest.
Population (On Foot)
Local command and control (C&C) centre receives a message from a driver who saw the smoke from the picnic fire. Fire fighters (FF) are dispatched to investigate. Fire fighters only recently finished attending other wildfires in the area.
(T): Move to location of incident.
(A): FF drive to site via local roads.
(I): Public report / C&C updates.
(L): Caught in congestion on road.
Response / Management
Person D left a small fire unattended. Fire develops after family has left the location. No threat perceived.
Incident

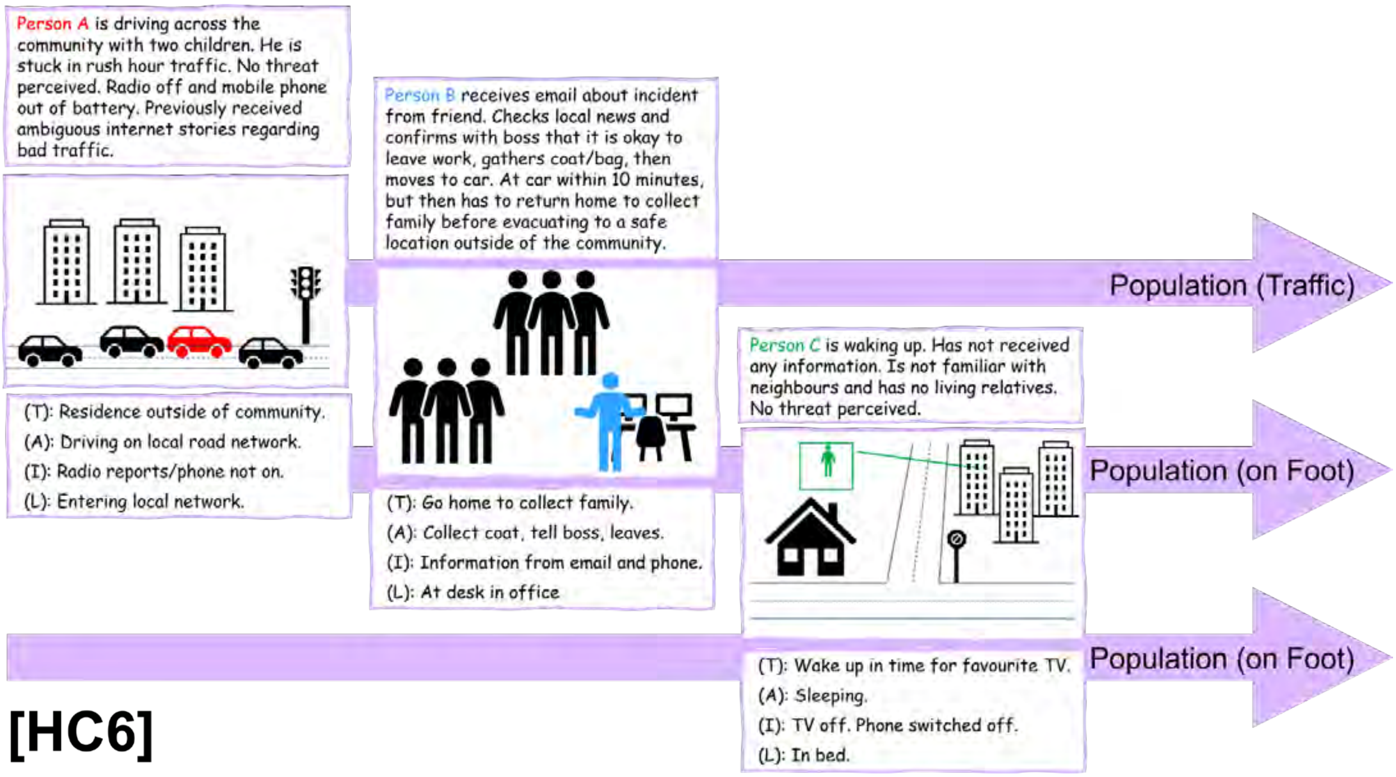
[HC3]

[HC4]

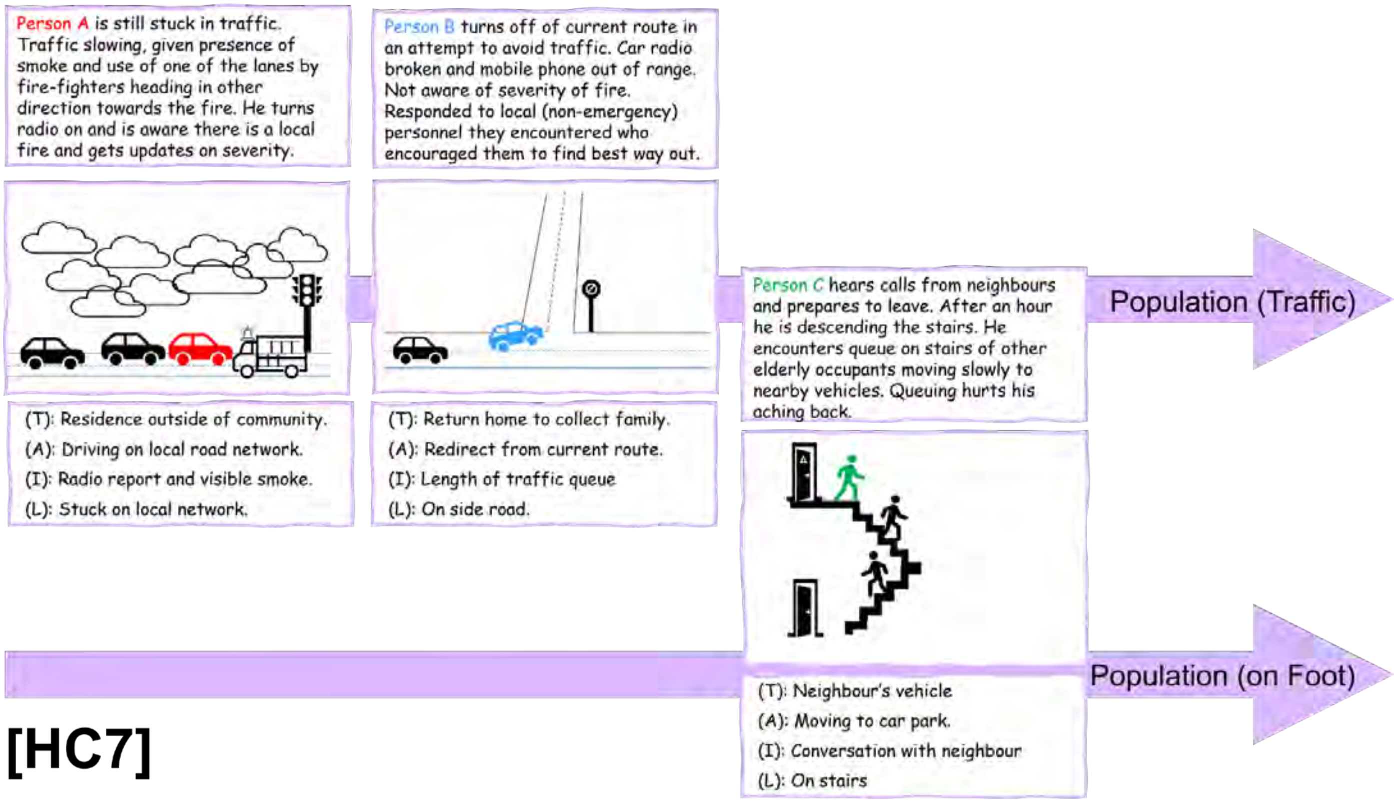

Traffic continues to flow routinely. No information available regarding the incident. No threat perceived.
Population (Traffic)
(T): Locations out of town.
(A): Following traffic.
(I): No information on incident.
(L): Local Roads.
Non-Government
Local command and control centre receives a message from fire chief on scene that fire is significant and requires additional resources
(T): Address fire.
(A): Dispatch FF to scene.
(I): Report from FF at scene.
(L): Command and Control centre.
Response / Management
Firefighters reach scene. Identify discarded materials and that fire has developed and needs to be addressed.
(T): Investigate fire reports.
(A): Attend location. Report scene.
(I): Hot day. Smoke reported.
(L): In forest.
Incident

[HC5]

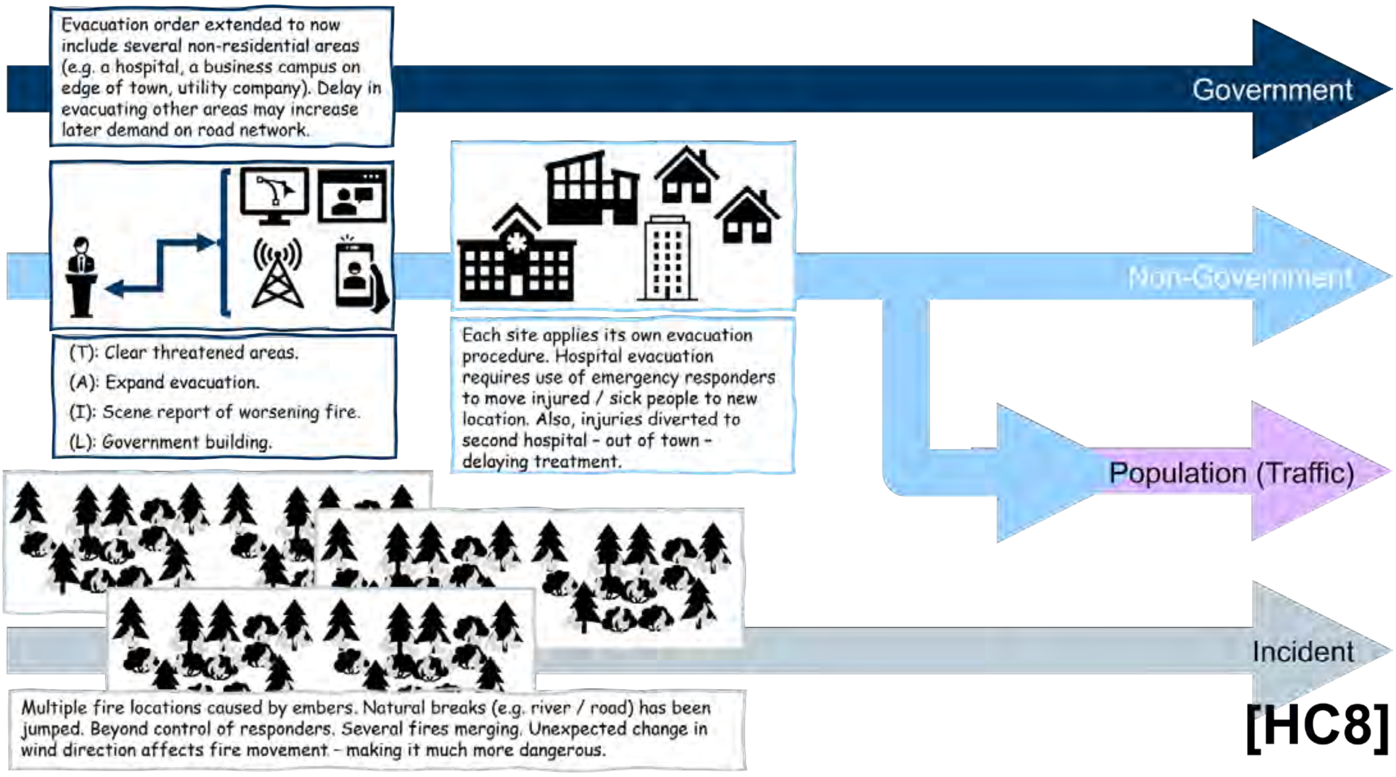

Local command and control centre contacts local authority to inform them that the fire is beyond their control and that they are deploying resources to safeguard other areas.
(T): Escalate response.
(A): Communicate fire spread.
(I): On scene fire reports.
(L): Command and Control centre.
Local authority become aware of situation and calls for an evacuation of those areas immediately affected by the fire. Small residential area of town affected.
Announcements made by several government levels (local / regional) and departments. Broadly consistent content although uncoordinated messaging. Information now also on social media.
Government
(T): Clear those at most risk.
(A): Mandate partial evacuation.
(I): Information from C&C.
(L): Government building.
Response / Management
Incident
Fire develops and spreads significantly. Fire-fighter efforts to control the fire have failed and it is not controllable at this location.


Person A is driving across the community with two children. He is stuck in rush hour traffic. No threat perceived. Radio off and mobile phone out of battery. Previously received ambiguous internet stories regarding bad traffic.
(T): Residence outside of community.
(A): Driving on local road network.
(I): Radio reports/phone not on.
(L): Entering local network.
Person B receives email about incident from friend. Checks local news and confirms with boss that it is okay to leave work, gathers coat/bag, then moves to car. At car within 10 minutes, but then has to return home to collect family before evacuating to a safe location outside of the community.
(T): Go home to collect family.
(A): Collect coat, tell boss, leaves.
(I): Information from email and phone.
(L): At desk in office
Population (Traffic)
Person C is waking up. Has not received any information. Is not familiar with neighbours and has no living relatives. No threat perceived.
Population (on Foot)
Population (on Foot)
(T): Wake up in time for favourite TV.
(A): Sleeping.
(I): TV off. Phone switched off.
(L): In bed.

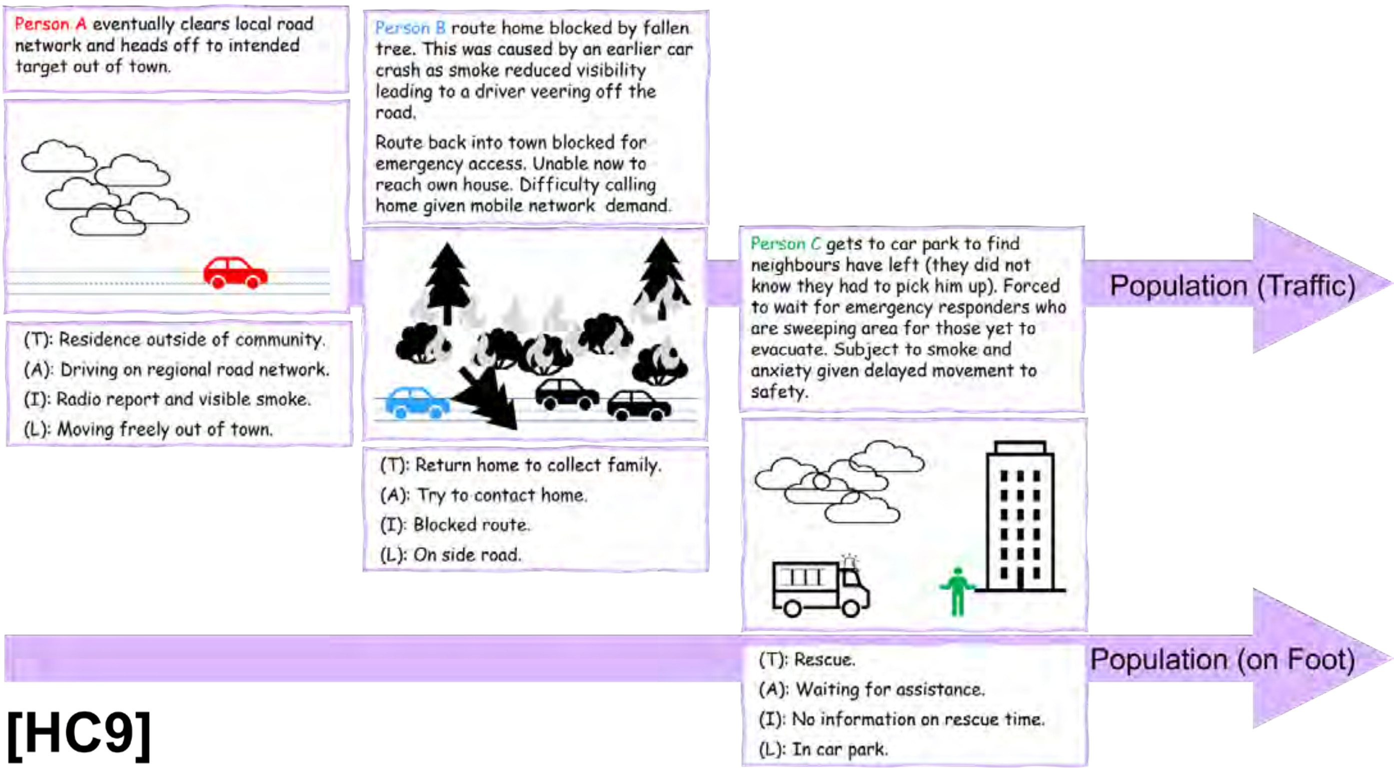
[HC6]


Person A is still stuck in traffic. Traffic slowing, given presence of smoke and use of one of the lanes by fire-fighters heading in other direction towards the fire. He turns radio on and is aware there is a local fire and gets updates on severity.
(T): Residence outside of community.
(A): Driving on local road network.
(I): Radio report and visible smoke.
(L): Stuck on local network.
Person B turns off of current route in an attempt to avoid traffic. Car radio broken and mobile phone out of range. Not aware of severity of fire. Responded to local (non-emergency) personnel they encountered who encouraged them to find best way out.
(T): Return home to collect family.
(A): Redirect from current route.
(I): Length of traffic queue
(L): On side road.
Person C hears calls from neighbours and prepares to leave. After an hour he is descending the stairs. He encounters queue on stairs of other elderly occupants moving slowly to nearby vehicles. Queuing hurts his aching back.
(T): Neighbour's vehicle
(A): Moving to car park.
(I): Conversation with neighbour
(L): On stairs
Population (Traffic)
Population (on Foot)

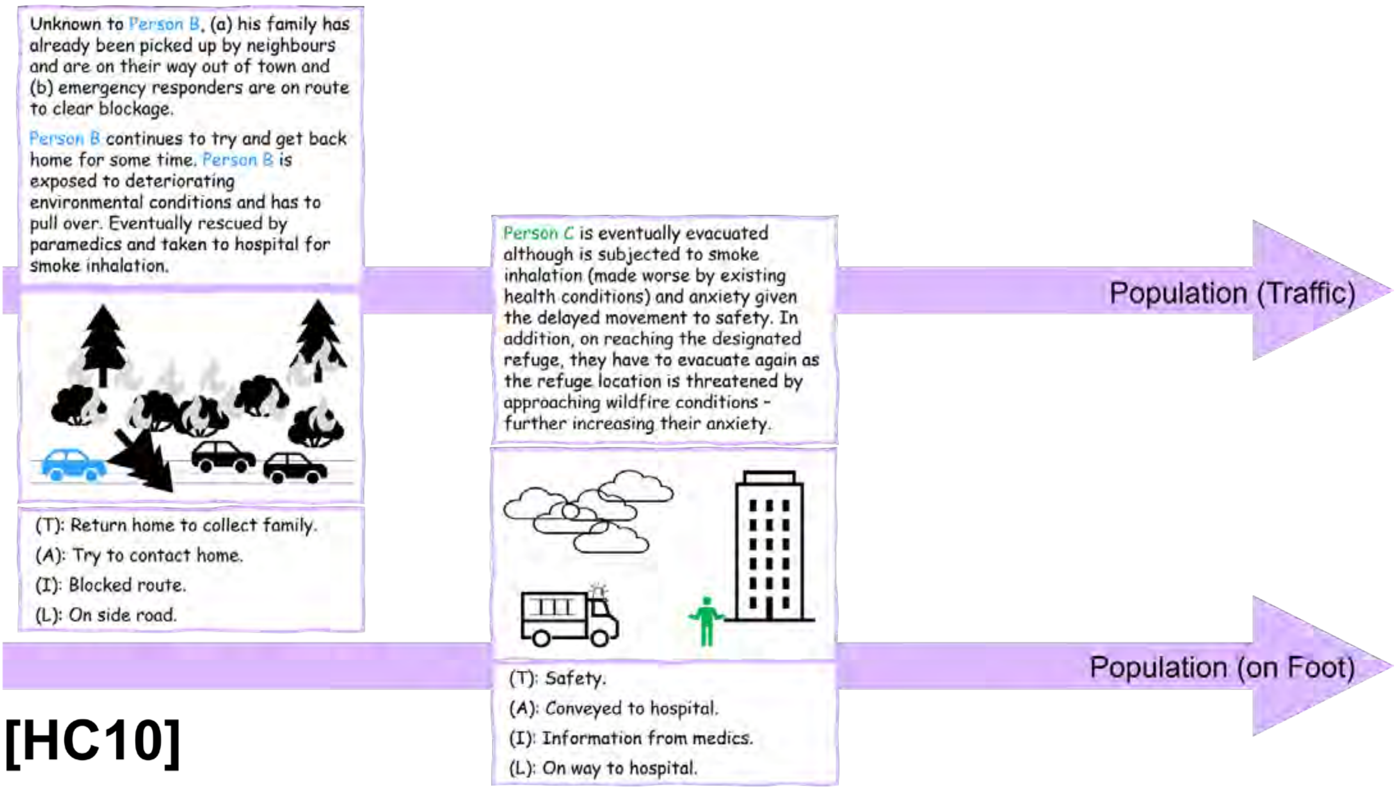
[HC7]


Evacuation order extended to now include several non-residential areas (e.g. a hospital, a business campus on edge of town, utility company). Delay in evacuating other areas may increase later demand on road network.
(T): Clear threatened areas.
(A): Expand evacuation.
(I): Scene report of worsening fire.
(L): Government building.
Each site applies its own evacuation procedure. Hospital evacuation requires use of emergency responders to move injured / sick people to new location. Also, injuries diverted to second hospital – out of town – delaying treatment.
Multiple fire locations caused by embers. Natural breaks (e.g. river / road) has been jumped. Beyond control of responders. Several fires merging. Unexpected change in wind direction affects fire movement – making it much more dangerous.
Government
Non-Government
Population (Traffic)
Incident

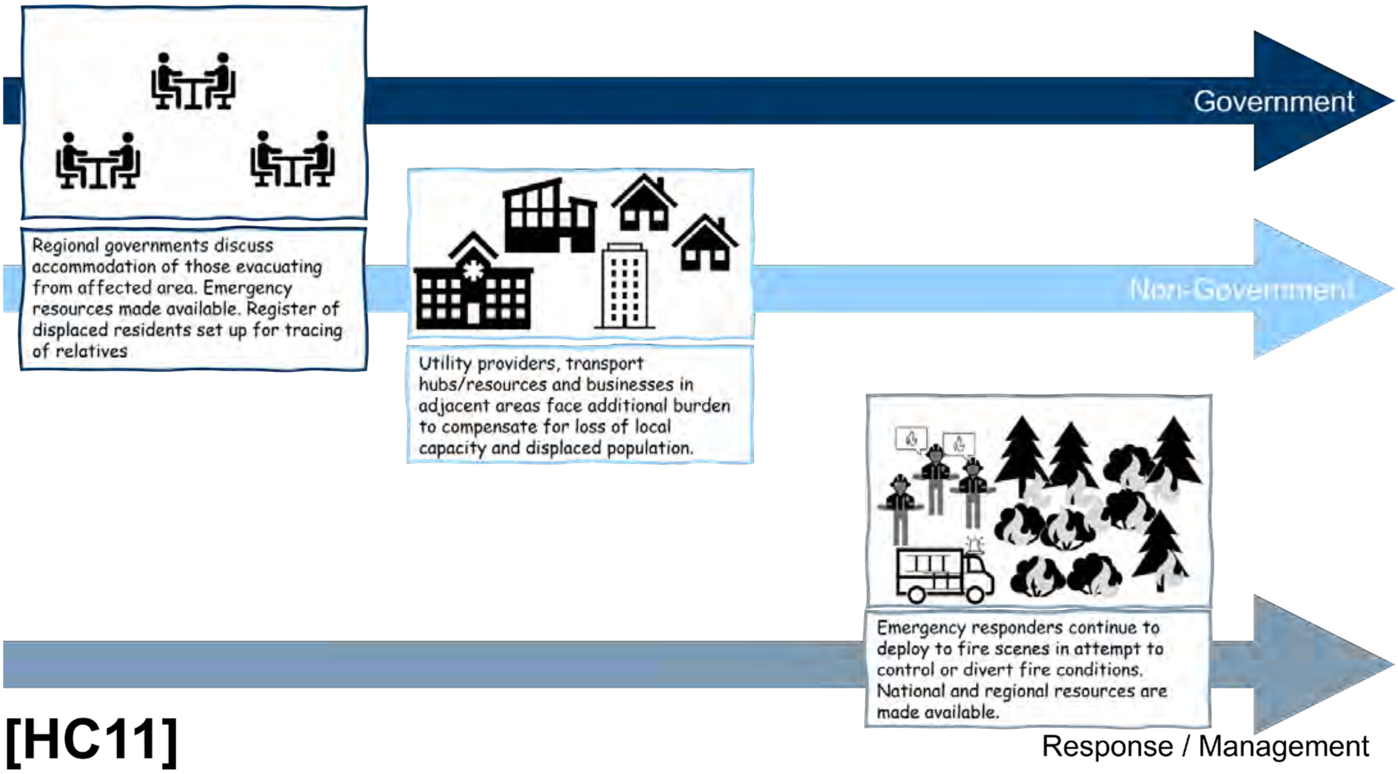
[HC8]


Person A eventually clears local road network and heads off to intended target out of town.
(T): Residence outside of community.
(A): Driving on regional road network.
(I): Radio report and visible smoke.
(L): Moving freely out of town.
Person B route home blocked by fallen tree. This was caused by an earlier car crash as smoke reduced visibility leading to a driver veering off the road.
Route back into town blocked for emergency access. Unable now to reach own house. Difficulty calling home given mobile network demand.
(T): Return home to collect family.
(A): Try to contact home.
(I): Blocked route.
(L): On side road.
Person C gets to car park to find neighbours have left (they did not know they had to pick him up). Forced to wait for emergency responders who are sweeping area for those yet to evacuate. Subject to smoke and anxiety given delayed movement to safety.
(T): Rescue.
(A): Waiting for assistance.
(I): No information on rescue time.
(L): In car park.
Population (Traffic)
Population (on Foot)

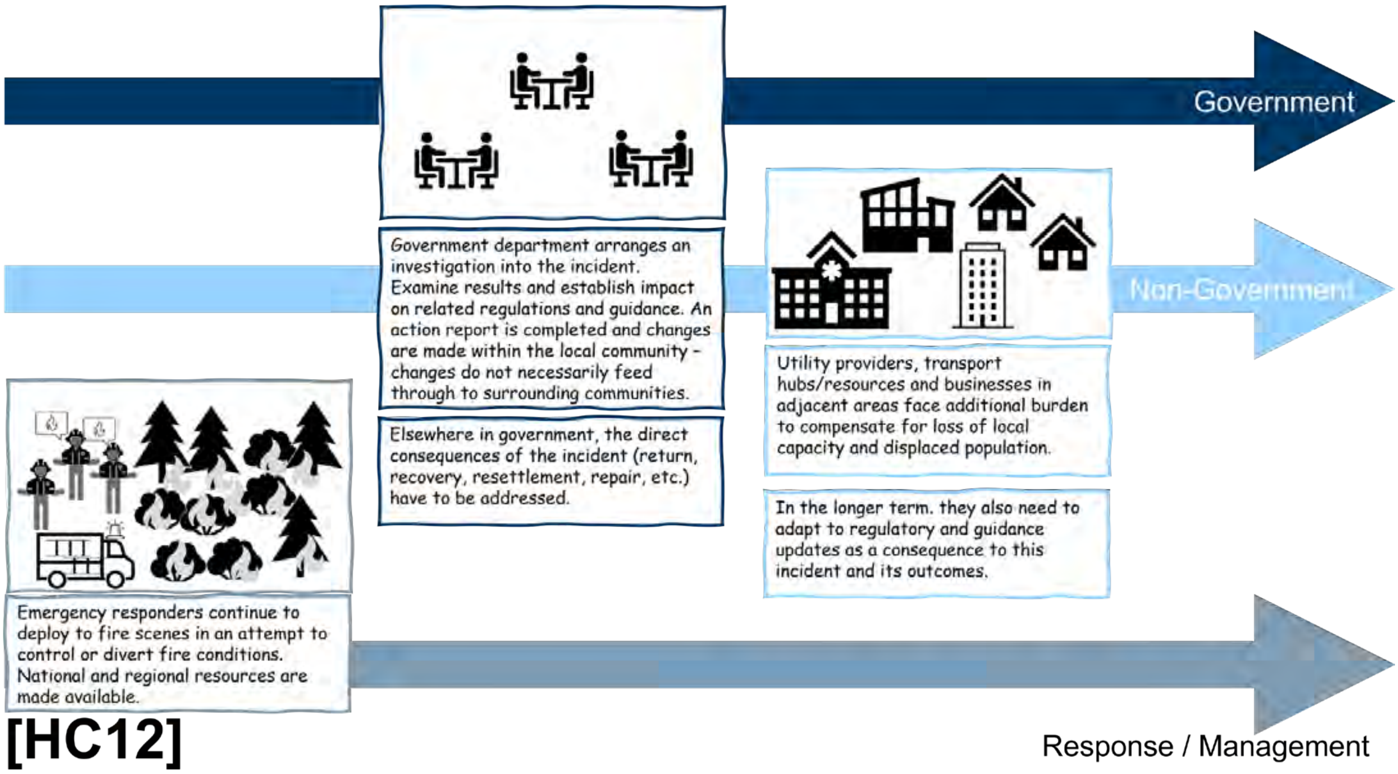
[HC9]


Unknown to Person B, (a) his family has already been picked up by neighbours and are on their way out of town and (b) emergency responders are on route to clear blockage.
Person B continues to try and get back home for some time. Person B is exposed to deteriorating environmental conditions and has to pull over. Eventually rescued by paramedics and taken to hospital for smoke inhalation.
(T): Return home to collect family.
(A): Try to contact home.
(I): Blocked route.
(L): On side road.
Person C is eventually evacuated although is subjected to smoke inhalation (made worse by existing health conditions) and anxiety given the delayed movement to safety. In addition, on reaching the designated refuge, they have to evacuate again as the refuge location is threatened by approaching wildfire conditions - further increasing their anxiety.
(T): Safety.
(A): Conveyed to hospital.
(I): Information from medics.
(L): On way to hospital.
Population (Traffic)
Population (on Foot)

[HC10]


Government
Non-Government
Response / Management
Regional governments discuss accommodation of those evacuating from affected area. Emergency resources made available. Register of displaced residents set up for tracing of relatives
Utility providers, transport hubs/resources and businesses in adjacent areas face additional burden to compensate for loss of local capacity and displaced population.
Emergency responders continue to deploy to fire scenes in attempt to control or divert fire conditions. National and regional resources are made available.

[HC11]


Government
Non-Government
Response / Management
Government department arranges an investigation into the incident. Examine results and establish impact on related regulations and guidance. An action report is completed and changes are made within the local community - changes do not necessarily feed through to surrounding communities.
Elsewhere in government, the direct consequences of the incident (return, recovery, resettlement, repair, etc.) have to be addressed.
Utility providers, transport hubs/resources and businesses in adjacent areas face additional burden to compensate for loss of local capacity and displaced population.
In the longer term, they also need to adapt to regulatory and guidance updates as a consequence to this incident and its outcomes.
Emergency responders continue to deploy to fire scenes in an attempt to control or divert fire conditions. National and regional resources are made available.

[HC12]

Section 3: Discussion and transferable learnings

Impact and regulatory response

The case studies (real and hypothetical) have shown that (1) large-scale wildfire evacuations are complex, (2) conditions evolve over time/place from interactions between social, physical, procedural and environmental factors, (3) seemingly local actions can have broader implications, (4) numerous agents/organisations are involved, and (5) information is likely inconsistent and perceived differently affecting the decision-making of those involved. Given the changing conditions, it is not possible to directly determine the effectiveness of designs and plans from historical incidents.

Complex systems involve the interaction of many actors and factors. To assess the evolution of complex systems typically requires the examination of this interaction – to establish the underlying dynamics of the system and the conditions produced. Similarly, wildfire evacuations might benefit from the application of models that capture key elements to explore the vulnerability of communities to wildfire events (where vulnerability represents the capacity of the community to cope with the conditions faced).

In the more mature building regulatory system, there are typically two approaches to fire regulations:

- Prescriptive approaches embed the knowledge and expertise gathered into a set of regulations that practitioners must follow within the scope of the regulatory framework. Given that the regulations are applied, a building design is deemed to be sufficiently safe for its intended use.
- Performance-based approach that requires an expert practitioner to quantify the evacuation performance achieved and compare it with projected fire conditions for a representative set of scenarios. Safety levels, in this context, must be demonstrated.

This performance-based approach (if it was applied to community evacuation) (a) allows for the effectiveness of different design solutions and emergency procedures to be compared for given scenarios, (b) allows for a variety of community designs to be addressed (given that they do not have to be previously accounted for within the scope of a prescriptive framework), and (c) provides an opportunity to diagnose where issues arise and suggest remedial actions.

Given the challenges posed by wildfire evacuation (in terms of changing conditions, evolving scenarios undermining historical insights, and multiple interacting components), future regulatory efforts may benefit from a performance-based approach. This is no panacea and requires robust engineering tools that capture core evacuation and fire dynamics, sufficient guidance on the use of these tools and oversight of this use. However, given the complexity of wildfire evacuation, performance assessment may be one of the only ways of identifying challenges, suggesting remedial actions and of determining the vulnerability of a community to the conditions that might arise.

Complexity of wildfire evacuations

Given the complexity of wildfire evacuations, we will likely need to use a model as a proxy – to simulate the evolving conditions. Imperfect though this may be, it may allow interactions and emergent conditions to be charted, key vulnerabilities to be identified, different scenarios / response to be explored and these to be prioritised and ranked accordingly – in terms of the threat posed.

Conditions evolve quickly and are sensitive to the factors present. Importantly, different communities are not equally vulnerable to the same incident, a single community's vulnerability evolves over the lifetime of an incident and that community may be subject to multiple scenarios. It is important for regulators and practitioners to have a means to quantify evacuation performance – to identify when and where problems arise and what are the most effective means of addressing them. Of course, this is not trivial – all models are simplifications. But it is important to shape best modelling practice – especially should we accept the complexity of such events and the need to assess performance on a case-by-case basis as a regulatory approach given the speed with which conditions change.

An example demonstration of modelling benefits – not available to a purely prescriptive approach – is described below with reference to **Figure 13**. In **Figure 13** (top row), the blue site has a built-up well-resourced population with some mid-rise structures and offices. The green site (**Figure 13** bottom row) is more rural – with fewer resources. Otherwise, the community footprint is the same shape and size in each case. The three versions of the blue and green sites have the same population, with different road connections – e.g., number, location and size of roads. Comparing horizontally, the same population may have a different evacuation potential given the different road networks available – even when exposed to the same fire. If we now compare vertically – across different site populations for the same road network design – the evacuees will exploit the same road network differently, given their capabilities, awareness and resources, e.g., decision-making, access to vehicles, etc. Quantifying evacuation performance helps determine the extent of these differences and their impact on the outcome. Quantifying these facts helps inform our design, planning and response decisions.

Modelling wildfire evacuations

Models will be necessary for the development of a performance-based approach to wildfire planning

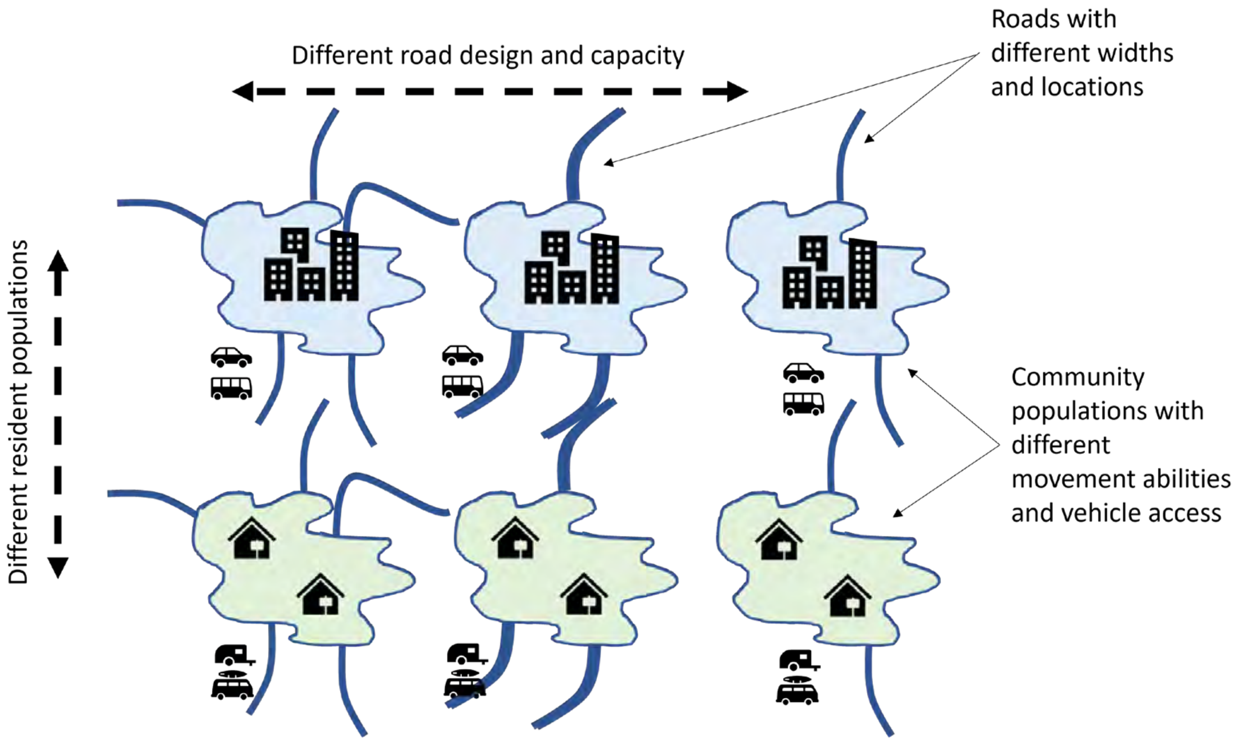


Figure 13: Depiction of comparative modelling utility.

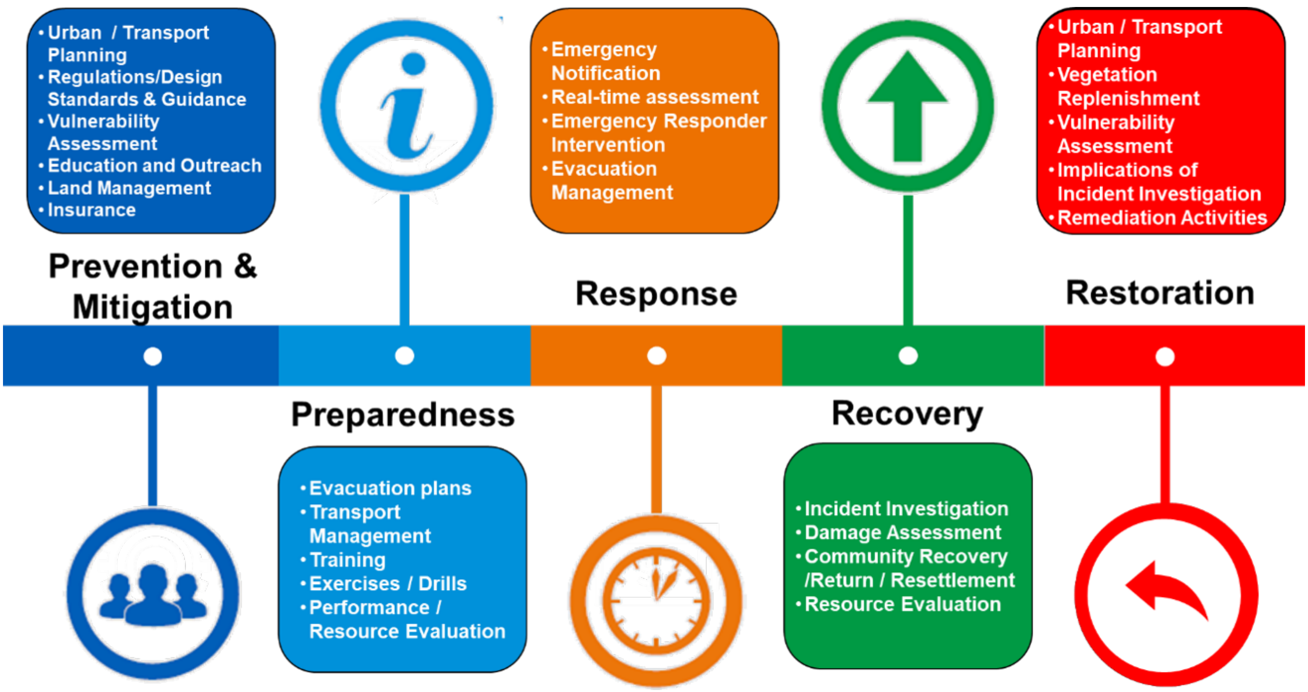


Figure 14: Models will be necessary to support a performance-based approach to wildfire planning.

to function, supporting community safety over time (see **Figure 14**).

They will also help communicate to the public and practitioners:

- The complexity of such events
- The sensitivity of outcomes to decisions made by those involved – public, responders, organisations
- How conditions can quickly and dramatically change
- How effective different measures might be
- How vulnerable different communities are to minor changes in conditions beyond their control.

These will help in community planning, outreach and education.

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Towards a simpler and safer nuclear sector: The 2005 THORP Internal Leak

By Prof Francis Livens, Dr William Bodel

Executive summary: In 2004, a leak of radioactive solution began at the THORP nuclear reprocessing plant due to failure of a single component. The component failure is unremarkable; what is most significant is that the leak progressed for eight months undetected because of an alarm-tolerant culture and inadequate working and monitoring practices.

Tags: nuclear, radioactive, reprocessing, energy, Sellafield, alarm-tolerance, monitoring, detection, instrumentation, United Kingdom

Section 1: Background and introduction

The UK has legally binding commitments to achieve Net Zero by 2050, and realising this ambition will likely require a significant contribution from nuclear energy. Safety is a common concern around nuclear technology, so the UK nuclear sector is heavily regulated. The nuclear sector will probably need to grow quickly and safely in order for the UK to reach its emissions reduction targets, so ensuring that regulation going forward is fit-for-purpose is of paramount importance.

Revisiting the THORP incident from 2005 in this case study will hopefully benefit those outside the nuclear sector who may gain something from the transferable learnings; it should also benefit the new generation entering the sector who, given that 16 years have passed, may not have the details of this incident as part of their consciousness.

Nuclear reprocessing

Nuclear energy generation exploits the fissile isotope of uranium (U-235) to generate energy and propagate a chain reaction. During operation, not all fissile material within nuclear fuel is utilised. Spent nuclear fuel[1] typically contains approximately:

- 1% plutonium
- 3.5% fission products
- 95.5% uranium, <1% of which is U-235

The reprocessing of spent fuel fulfils two roles: Firstly, it reduces the volume of high level nuclear waste; and secondly it allows for extraction of uranium and plutonium to recycle into new fuel.

In the UK, reprocessing nuclear fuel uses a chemical process known as PUREX (Plutonium Uranium Reduction Extraction) [1] which comprises spent fuel storage, conversion to solution, chemical separation of uranium and plutonium from other elements, conversion to solid oxides, and also treatment of any waste.

The Thermal Oxide Reprocessing Plant (THORP) at Sellafield in Cumbria is the UK's most recent nuclear fuel reprocessing plant, opening in 1994 to handle both domestic and foreign fuel. **Figure 1** provides an overview of the processes which make up the operations at THORP. THORP ceased operation in 2018 in response to reduced reprocessing demand; further spent fuel is now stored on site within storage ponds.

In 2005 a leak of radioactive solution into secondary containment was discovered at THORP. In 1990, the International Atomic Energy Agency (IAEA) developed the International Nuclear and Radiological Event Scale (INES) [2] to help convey the severity of incidents at nuclear installations. The 2005 leak at THORP was classified INES level 3 (out of 7); a serious incident (and near-accident).

Section 2: Analysis and insights

The 2005 THORP incident

The part of the process involved in the incident was the first conversion stage. Here, in the Head End plant, spent nuclear fuel is sheared before dissolution in nitric acid, forming a product liquor. The liquor is then centrifuged and the uranium and plutonium content measured before chemical separation begins.

Part of the feed clarification cell, Vessel V2207B, is a 23 m^3 Head End accountancy tank, where centrifuged liquor is weighed. Nozzle N5 (**Figure 2**) connected the centrifuges to Vessel V2207B and it was the failure of this nozzle that led to the leak of radioactive liquor.

The operator company, British Nuclear Group Sellafield Limited (BNGSL), learned of the leak on 20 April 2005 and reported

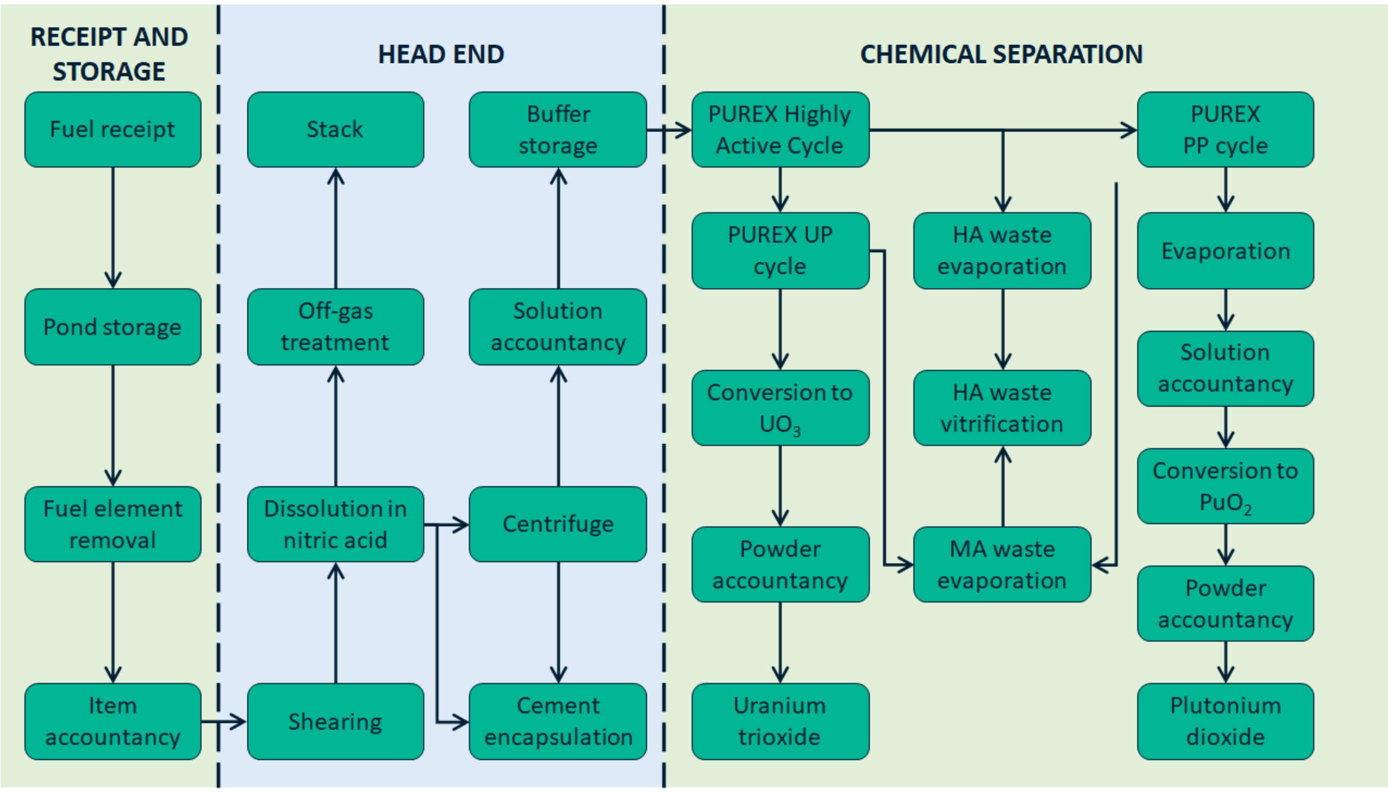

Figure 1: Overview of the THORP processes. The Head End plant was where the events which caused the THORP incident took place. In the Head End plant, spent nuclear fuel is sheared before dissolution in nitric acid, forming a product liquor. The liquor is then centrifuged and the uranium and plutonium content measured before chemical separation begins. A nozzle connecting a centrifuge to an accountancy tank failed, resulting in the leak of dissolver liquor. (Source: adapted from [8])

it to the UK Health and Safety Executive (HSE). This was, however, at least eight months after the leak had started, by which point 83,000 litres of dissolver liquor had leaked onto the floor of the feed clarification cell. This volume of dissolver liquor contained 22 tonnes of uranium and 160 kg of plutonium. The volume of leaked liquor was 3.5 times that of the capacity of the intended destination accountancy tank. Remote camera investigation after locating the leak revealed that the corrosive liquor had damaged the support frame steelwork.

All leaked material from the failed nozzle was contained within the feed clarification cell and returned to the primary containment during the recovery operation in May 2005. No injuries resulted from the incident and no leak of material from the secondary containment occurred. THORP was closed following the incident and was granted permission to restart operations in January 2007, 20 months after the discovery of the leak. BNGSL pleaded guilty to breaches of site licence conditions and was fined £500,000.

Criticality risk

The major safety concern in accidents involving fissile material is the potential for a criticality accident; that is, an unintentional uncontrolled nuclear fission chain reaction. Criticality accidents require a greater than critical mass of fissile material arranged in a specific geometry and can lead to the release of fatal radiation doses and, in some cases, serious mechanical damage [3].

The criticality safety case for the feed clarification cells covered multiple accident conditions, though a major leak was considered unlikely. Given the scale and duration of the leak, the regulator concluded that "the effectiveness of some of the measures in place to prevent criticality could not be guaranteed." [4].

The "cause" of the leak

Mechanically, the cause of the shearing of Nozzle N5 from its vessel was attributed to fatigue failure from repeated and continued oscillation of the accountancy tank, which is suspended to allow for weighing of the vessel.

Normal operation of the accountancy tank involves blending the dissolver liquor within it using a pulse jet and, as a consequence, the agitated contents initiate motion of the tank. This movement was accommodated in the original design of the cell with a restraining mechanism, but a modification to the operation of the vessel in 1997 removed the restraint, enabling the failure.

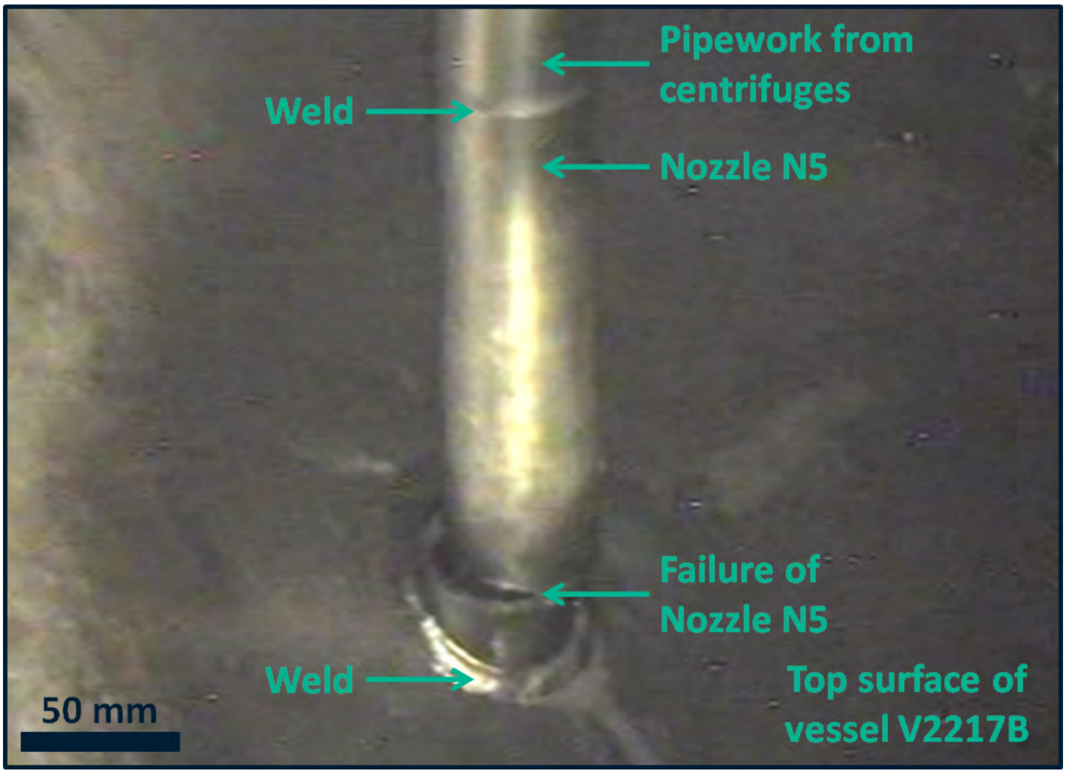

Figure 2: Image showing the severance of Nozzle N5 from the accountancy tank into which the dissolver liquor should have fed. (Source: adapted from [4])

The failure of the system, however, goes beyond the failure of a single component. Leaks are to be expected when handling fluids; the ultimate failure of the system was not that the leak occurred, but that it went undetected for at least eight months.

Leak detection systems

The feed clarification cell was designed as a secondary containment in the event of any leak and is capable of holding 250 m^3 of fluid (ie the cell was at one third full capacity when the leak was discovered). Sumps within the cell, where leaked solution would accumulate, are fitted with pneumercators which measure the depths of any leaked fluid present and sound alarms when operating outside of intended conditions.

The sump pneumercators require a residual depth of acid within the sump to operate effectively, and 'low' alarms indicate if the acid needs replenishing. 'High' alarms indicate that the depth is too high and therefore suggest a leak of dissolver liquor into a sump.

In addition to the pneumercators, THORP operational arrangements dictated that samples were to be taken from the sumps for analysis every three months. Detection of uranium within the samples would indicate the presence of a leak of dissolver liquor.

End-of-campaign stocktake discrepancies

The leak which began in or before August 2004 went undetected by these leak detection systems and it was only when accountancy discrepancies were noticed in end-of-campaign figures that an investigation was initiated and the leak discovered. The accountancy figures rely on sampling results and complex calculations which can take over a month to produce after the end of a campaign. This was responsible for the delay between the start of the leak and discrepancies appearing on the books.

It should be noted that the accountancy process was not intended to contribute to plant monitoring; its role was to ensure that international non-proliferation commitments are being met.

Uranium sampling

The presence of uranium within the samples collected quarterly from the sump would have indicated the presence of a leak into the feed clarification cell.

According to records, difficulties in obtaining samples from the buffer sump led to several unsuccessful collections, as far back as 1995. Requests for samples were routinely made and failed collections reported, but no action was taken. The lack of successful routine sampling was not deemed a priority, with collecting operational samples to continue processing taking precedence.

Between November 2003 and April 2005, only one successful buffer sump sample was collected, in

August 2004, which measured the presence of 50 g of uranium per litre. Samples taken from elsewhere in the cell in Q4 2004 and Q1 2005 also showed a presence of uranium.

This limited sampling should still have been enough to suggest the presence of a leak. Confusion between teams as to which team was responsible for this monitoring and data analysis inhibited the response, as did the inability of potential monitoring staff to use the data interpretation software due to lack of training.

Leak instrumentation and maintenance

Even after the discovery of the leak, with 83 m^3 of dissolver product liquor present within the feed clarification cell, the relevant pneumercator was still not recording high liquid levels. The error was caused by a stuck float within the sump pneumercator and it was later discovered that simply tapping the tube containing the float caused the device to measure accurately.

Maintenance instructions omitted the necessity to check the float (which would eventually become stuck), focusing instead on calibration and pressure responses. As such, no proof of correct operation of the instrument as a whole was required during maintenance. Checking historical instrument data for inconsistencies also did not form part of the maintenance process.

The absence of comprehensively detailed maintenance instructions meant that effective maintenance relied more on the skill of the staff. The use of non-specialist staff for maintenance reduced the ability to identify problems with instrumentation.

The investigation also raised questions regarding logging job requests and their role in best practice. Maintenance of instruments was carried out following direct verbal requests, without being routed through management. Staff suggested that this practice had become common practice following reductions in employees.

Alarm-tolerant culture

During the following investigation, the pneumercator in question had been in 'low' alarm modes for 85% of its operating period since 2000. This was attributed to the difficulty involved in adding acid to the sump, and in achieving the correct sump depth so as to not trigger either the 'low' or 'high' level alarms.

The safety case for the feed clarification cell did not recognise a 'low' sump alarm as significant, unlike a 'high' alarm. Instruments were operating routinely under 'low' alarm status.

Alarms from all areas of the plant (not just local alarms) are displayed on the plant's distributed control system. As further alarms activated, existing alarms would be pushed down the list, making them harder to observe and thus long-standing alarms would reduce in priority.

The 1998 THORP leak

This was not the first such leak during the operation of THORP. In 1998, events similar to those in 2005 occurred, when eroded pipework in the dissolver cell resulted in a leak into the sump.

An internal investigation followed, which provided 28 recommendations, most concerning sump monitoring, sampling and the pneumercators. No formal record was kept as to what extent the 28 recommendations had been implemented. Given the similarity between the two incidents, it is likely that proper implementation of the 1998 recommendations would have prevented the more serious incident of 2005.

Section 3: Discussion and transferable learnings

The THORP safety case stated that any leaks of dissolver product liquor in the feed clarification cell would be detected within a few days. In fact, when such a leak did happen it took over eight months to detect, and through a process never intended to be used for plant monitoring.

The cause of the leak was modification to the accounting vessel which did not consider the detrimental impact this would have on the connecting pipework, ultimately causing a guillotine failure on Nozzle N5. Full assessment of the impact of any design changes should have been carried out, with consideration paid to understanding the original design before any modifications were carried out. The importance of second-order thinking eloquently described by G.K. Chesterton with his heuristic fence[2] applies as much in engineering as it does to policy decisions.

The lack of appreciation of the restraint apparatus and its subsequent removal constituted an unconscious design change, made during maintenance cycles, and was therefore beyond the scope of the normal change control procedures that usually exist for design. Design changes feature in the stories of many major accidents; the incident at THORP is one further example.

Even combined with the difficulties of sampling from the buffer sump and accurately adding the correct volume of acid, these design flaws did not cause the THORP incident. The incident, and particularly its severity, resulted from the human and organisational failings which allowed the leak to continue for over eight months.

Numerous failures are evident, all within the management and task and technical layers (ie none within the governance layer) [5, Fig. 5]. The running failure theme of the incident is that of human-system interaction [5, p. 89]; operators' understanding of the system was continually at odds with the true system state.

The confusion between teams as to who was responsible for the monitoring and data analysis of samples taken from sumps prevented the identification of 50 g/l of uranium present, and by consequence, the existence of a leak. Having no single owner [5, p. 89] of tasks may also have led to staff being improperly trained in the use of the relevant data interpretation software. Clearly defining roles would have helped ensure tasks were fully carried out and separating the alarms displayed on the distributed control system into those relevant to each area of the plant would have kept them on display and maintained their priority status.

Most failings resulted from management and/or operators not following protocols that had been put in place. Two clear exceptions to this were that no proof of correct overall operation was required during routine pneumercator maintenance and that checking historical instrument data for inconsistencies did not form part of the maintenance process. Inclusion of these two tasks within the maintenance process would have identified the ineffectiveness of the flawed pneumercator.

Lean organisational operation [5, p. 96], shedding excess capability to preserve the minimum required to carry out business operations makes enterprises less resilient. Inadequately retraining surplus electricians as instrument maintenance staff ensured that they were ill-placed to compensate for the sub-optimal protocols mentioned above. Dedicated instrument personnel might have identified that there was a problem with instruments over a long time period.

Competing objectives [5, p. 90] sacrificed a focus on obtaining successful routine sampling, in favour of the collection of operational samples, while the significance of 'high' alarms within the safety case over 'low' alarms contributed heavily to alarm tolerance. The safety case was inadequate with regards to 'low' alarms so their significance was not understood by supervisors.

The remaining failures all exist at the managerial level and can be grouped into three principal areas:

1. Alarm tolerance

The culture of the Head End plant was to routinely allow instruments to operate continuously under alarm. Pneumercator alarms were distinguished between 'low' and 'high', with 'low' alarms not deemed urgent enough to warrant investigation to resolve the fault. The pneumercator at fault in this incident had been in 'low' alarm modes for 85% of its operating period over the preceding four years. The extent of this demonstrates that the problem was systemic, and not the fault of single individuals.

Finding ways to address the alarms would have been far preferable to tolerating their continued operation. With so many continuous alarms signalling, it was left to the supervisor to assess what was most pressing, resulting in a competency gap from the unmanageable complexity [5, p. 90].

2. Inadequate record-keeping

Requests for sump samples were routinely made and their many failed collections were reported. Despite this, no action was taken. In addition, maintenance of instruments was carried out following direct verbal request, without being routed through management. With no paper trail of written requests and reports, no systematic check of plant conditions could be carried out.

Formalised checking regimes would have potentially enabled managers to spot trends of dysfunctional instrumentation within the plant and act accordingly.

3. Failure to learn from previous incidents

Perhaps most worrying was the similar, but less severe, incident in the Head End plant in 1998. Although the resulting internal investigation issued 28 recommendations, there was no formal record of the extent of implementation. The investigation following the 2005 incident stated that proper implementation of the 1998 recommendations would have prevented the more serious incident of 2005. It is important to ensure that the lessons from the 2005 incident have been learned and the recommendations continue to be followed.

Effects on the site

In response to the post-incident investigation by the HSE, THORP implemented a range of changes to safety culture:

- An updated plant safety case
- Staff knowledge development workshops
- Operating experience and training
- Organisational reviews for leadership roles
- An increased focus on nuclear safety.

One of the benefits of revisiting the 2005 THORP incident more than 16 years later is that it is possible to see whether the learnings from the incident are still being applied and feature in current staff training. While THORP closed in 2018, much nuclear work continues elsewhere around the Sellafield site, and it is here that the generic lessons can still be applied.

The lessons from the 2005 THORP incident are reportedly being kept alive across the site and the learnings feature throughout the site's culture as Learning from Experience.

Robust hazard and fault identification is essential to any demonstration of safety and forms part of the management systems and processes, contributes to the Safety Case and to any subsequent Periodic Safety Review.

A range of activities and studies are applied to identify hazards, with the approach selected dependant on the size of the project or task. Examples include Hazard and Operability Studies, Failure Modes and Effects Analyses as well as plant walk-downs, task analyses and revisiting previous studies. Importantly, Learning from Experience is specifically identified in all nuclear industry management systems.

The UK nuclear industry is closely regulated by Government's Office for Nuclear Regulation and has robust oversight from nuclear safety and security committees; while industrial bodies such as the Safety Directors Forum provide insight into wider learning and their Good Practice Guides draw upon and share Learning from Experience across the sector. Certification bodies, such as Lloyd's Register and the World Association of Nuclear Operators (WANO), have their own independent mechanisms incorporating Learning from Experience which contribute to broadening safety culture. Following the 2005 incident, the THORP team instigated daily nuclear safety calls; the forerunner to the daily fleet call which forms part of WANO best practice.

More recently, the industry has made a distinction between leadership and management. Sellafield Ltd has recently released a revised Nuclear Professionalism Standards and Expectations document [6] which aims to provide clarity of purpose for the site. The document prioritises 'how to think' rather than solely prescribing safety and engineering processes that identify 'what to do' under rigidly specific circumstances.

Leadership and project academies have their curriculum built upon Learning from Experience and focus on case studies, such as the THORP incident of 2005, to provoke reflection on the past and stimulate thinking on how this might impact the nuclear site in the future.

Too often, Learning from Experience leads to straightforward modification of procedures, rather than any deeper cultural change. However, THORP operated without incident for the 13 years up until the closure of the plant in 2018. If the experience from the 2005 incident led to real change in attitudes and culture, driven from the top of the organisation, then this can be considered a successful Learning from Experience model.

With new growth expected in the UK nuclear sector in the coming decades, the safety lessons from incidents such as that at THORP in 2005 must continue to feed into future nuclear safety culture, long after the plants where the incidents took place cease to operate.

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Endnotes

1. From a typical light water reactor.
2. Chesterton's Fence [7], he describes, "was not set up by somnambulists who built it in their sleep". He insists that before removing a structure that at first seems useless, one must first establish the *full* purpose of the structure; and only then can it be safely removed without fear of unexpected consequences.

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Bexley train crash – a system failure

By Dr Chris Elliott MBE FREng

Executive summary: A goods train derailed with three independent causes: poor track maintenance, overloaded wagons, and excess speed. The "holes in the Swiss cheese" lined up, and each hole had many complex underlying causes. Safety of a complex system must be planned and executed as a system, not as separate pieces.

Tags: train derailment, train accident, transport, root cause analysis, accident inquiry, inadequate resources, contractual complexity, political priorities, systematic planning, United Kingdom.

Section 1: Background and introduction

On 4 February 1997 a goods train derailed at Bexley. Four people were seriously injured and there was extensive damage. HSE investigated the accident[1] and subsequently prosecuted the track owner, operator and maintainer (Railtrack and its contractor) and the train operator.

The accident is informative because it had three immediate causes and it is likely that all three were necessary for the accident to happen.

1. Poor track maintenance: the longitudinal timbers supporting the track on the bridge were rotten, allowing the rails to move ('gauge spreading')
2. Overload: the wagon that derailed was estimated to be 30% over the permitted weight for a line rated for the heaviest loads (RA10); this line was rated below that (RA8).
3. Overspeed: the inquiry did not estimate the impact of the overspeed of around 37% but it is reasonable to assume that the dynamic loads are at least proportional to speed so the dynamic effect was as great as the static overload.

However, the chain of causation is more complex because each immediate cause had root causes:

Maintenance

- Railtrack (principal duty-holder) had failed to follow its audit plan
- SEIMCL (maintenance contractor) had not communicated well with Railtrack
- There was major restructuring of staff in SEIMCL and a critical post was vacant
- The condition of the sleepers was so poor that they could not have decayed to that state within the three years since Railtrack inherited responsibility, they must have already been defective when maintained by British Rail

Overload

- The wagons had carried ballast, less dense than the spoil carried on this day
- The loaders were told to use only 75% of the volume of the wagon, without any justification for that value.

Overspeed

- The speedometers in the cabs were under-reading by ~ 10%
- The driver was not aware of the local rule regarding the speed of goods vehicles (which was lower than the 'signed' speed)
- The driver had been trained at a centre that systematically did not teach this rule.

Section 2: Analysis and insights

At its simplest level, this is a classic system failure. It is well described by Reason's 'Swiss cheese' model in which holes in three layers of protection (track maintenance, load control and speed control) lined up to allow the accident to occur. Many trains had passed over that section of track without derailing, it is likely that some were overloaded and that some were speeding, but a train that combined all three elements caused a structural failure.

It also illustrates the error of latching on to the immediate causes. All three had deeper root causes that reflected failures of management systems. The contractual arrangements for track maintenance were complex and badly defined, with inadequate resources and poor information flow. The loaders were poorly instructed and the system for instructing them was inadequate, with inadequate review and quality control. There was no control on speedometers and there was a long-standing failure to train drivers of freight trains in the rules across all parts of the network. The inquiry also found other safety failings, such as the incorrect tare weight on one of the wagons, but concluded that these did not contribute to the accident.

The contractual complexity is illustrated by the train itself – the wagon that started the derailment was owned by CAIB UK Ltd and operated by English, Welsh & Scottish Railways Ltd and the driver was on contract from Connex South Central.

A complex contractual chain (or more accurately network) is not intrinsically unsafe – civil aviation has a very complex contractual structure without compromising safety. However, it demands proper planning, adequate resources and especially very careful management of the transition from a simple integrated regime to a fragmented regime bound together by contracts. All three were absent in the transition from vertically-integrated British Rail to the fragmented privatised railway.

The over-riding message is that successful safety management of a complex system must be planned and executed as a system, not as a set of separate measures.

Section 3: Discussion and transferable learnings

This case study illustrates the issues outlined by the York Framework[2], depicted in **Figure 1**, previously released by the Safer Complex Systems mission:

Causes of system complexity

- Railways are intrinsically complex and rely for safe operation on clear and unambiguous rules that are strictly followed
- The railway had been broken into many independent companies
- Regulatory structures were weak, relying on duty-holders without close oversight
- Technical complexity is easily recognised, management complexity is not

Consequences of system complexity

- No one person 'owned' the issues
- Unsound practices were allowed to persist

Design-time controls

- Track speed and loading ratings were not known or enforced
- No procedure existed to verify speedometers, or if it did, it was not followed
- Decisions were arbitrary and not subject to review
- Audits were not conducted

Operation-time controls

- Key staff (loaders, drivers, maintenance planners) were not properly briefed
- Inadequately-trained drivers were used

Exacerbating factors

- General sense of confusion following the definition and implementation of the fragmentation of the railway
- Failure to replace previous informal practices that relied on personal relationships with a systematic safety management system

This accident raises many wider issues because it can be used to shine a light on some of the problems that the UK's legal system has when dealing with system issues.

Criminal law

The test of criminal liability is that the defendant did, and in most cases also intended to do, the act 'beyond reasonable doubt'. In this case, it is hard to see any doubt that all three of the failures (maintenance, overload and speed) passed this test but only two were prosecuted. Arguably the one that was not prosecuted (speed) is the most serious because it was systematic and long-standing.

The test in the Health and Safety at Work Act is that the defendant did everything reasonable to reduce risk (ALARP). This is a powerful and elegant rule but struggles with statistical causes and frequently uses an irrational concept of 'reasonable'. In this case, it may not have been reasonable for the duty-holders to have put right the flaws in their systems, even

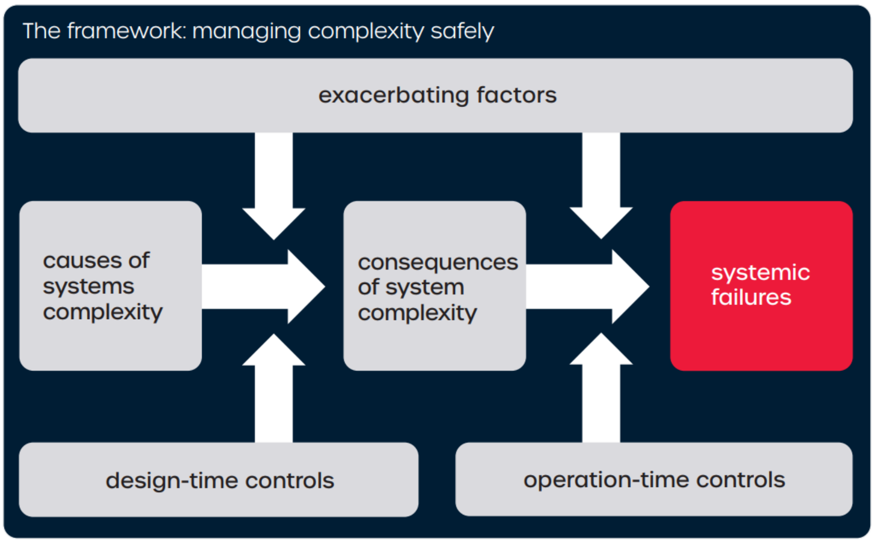

Figure 1: The York Framework[2].

though they are obvious with hindsight, if they were driven by political pressures and constraints and had inherited a backlog of maintenance and lack of management systems from a quite different legal structure.

Although railways rely on strictly following rules, it is impossible to encode those rules in a legal framework, which will always lag behind innovation in practices and technology. This accident occurred before rail regulation adopted the 'New Approach' of general legal principles and industry-made detailed rules. After around 30 years of successfully applying this approach, there are disturbing signs of returning to a prescriptive regime, for example for autonomous road vehicles

Health and safety law in the UK is largely based on the seminal report of the committee chaired by Lord Robens in 1972. That report argued that complicated prescriptive standards should be replaced by a duty on each employer to strive to eliminate risks to workers and others, so far as is reasonably practicable. However, the report states in paragraph 182:

> *We accept that transport safety is a vast study in its own right, involving many technical problems of a highly-specialised nature. Provisions for the safety and health of those engaged in flying aircraft, driving trains, lorries and so on clearly cannot be considered in isolation from a whole complex of special considerations such as the constraints imposed by the design of transport vehicles; the circumstances in which they operate which include many eventualities beyond the control of an employer; and the predominant need – in terms of numbers at risk – to safeguard the travelling public and the public generally. We accept that these matters must be dealt with within transport legislation.*

Paragraph 475 of the report summarises the conclusion:

> *The legislation .. should not apply to the normal use of the highway, to domestic service, or to transport workers whilst actually engaged in transport operations.*

Lord Robens and his committee understood that it was not appropriate to hold one person to account for failures of a system over which he does not have control.

Despite Lord Robens' clear statement, the consequent HSWA is applied to systems. Also the UK is unusual in that it is underpinned by criminal, not civil law.

That is fine when the breach is simple and obvious. If an employer does not give his staff adequate Personal Protective Equipment for work in a hazardous environment, he is guilty unless he can prove that it was not reasonably practicable to have done more. It is much harder to enforce when the harm is an emergent property of the action of many employers: A + B → C

Attempts to reconcile the criminal legal system with the word 'reasonable' have led to several other distortions that may be particularly unjust when applied to system failures:

- using ill-defined concepts like 'gross disproportion'
- in a complete inversion of normal legal logic, arguing that a breach may be serious enough to constitute a crime but not serious enough to constitute a tort/civil wrong
- placing the onus of proving that an alternative was not reasonably practicable on the defendant, thus creating a presumption of guilt until proven innocent.

Conclusion: The UK's safety law, including HSWA, was never intended to, and is poorly constructed to, apply to systems

Civil law

Tort law relies on the concept of causation – this requires that the outcome should be sufficiently proximate to an action for that action to be causal. Where the evidence is only statistical, an event must be more than 50% likely to have been the cause for causation to be found. Where three immediate causes together led to an accident, it is arguable that none contributed more than 33% so there is no causation. In a 2006 paper[3] the present author wrote:

> *But what happens when the risk arises solely from the interaction of the parts of the system. You can't then apportion the risk to each part – it makes no more sense than to try to describe the sound of one hand clapping.*

The tortious principle of causation has many weaknesses when applied to complex failures, especially when there are known and unknown unknowns and when it has to deal with the apportionment of risk. The principle is that there is no liability unless the failure is more than 50% likely to have caused the harm – there is no allowance for loss of expectation value.

If liability arises, it is for the condition of the victim at the time, not for the condition of a normal victim (known as the egg shell skull). Although this was not a consideration here, all three of the causes had 'egg-shell' conditions unknown to the other players.

Civil liability is determined on a balance of probabilities, which is hard to determine in a three-cause event.

Civil liability often hinges on the question of whether the victim would have suffered 'but for' the defendant's actions. This accident illustrates the difficulty of applying the 'but for test' in a system failure.

Contract law is better on probability but is still challenged by causation.

Conclusion: Civil law is poorly constructed to apply to systems.

Accident investigation

This accident was investigated by HSE, which then prosecuted two of the companies that it investigated. Since then rail accidents have been investigated by the Rail Accident Investigation Branch. RAIB's website states 'Our investigations are focused solely on improving safety. We are not a prosecuting body and do not apportion blame or liability.' However, legal protections for witnesses are weaker than for the Air and Marine equivalent bodies, an essential feature of the success of their impact on safety.

Two fundamental tools to improve the safety of systems are: confidential but not anonymous reporting of accidents and incidents; and impartial expert investigation after an accident to find the root cause.

Both depend on a willingness to be open and share knowledge and experiences without fear of recrimination, within a 'just culture'. The concept is best developed in transport. The three bodies in the UK that investigate transport accidents have an overriding duty to identify causes, not blame. Air and maritime investigations have legal protections that ensure that their reports and opinions may not be used in legal proceedings concerned with blame or liability. Rail reports may be admitted to such proceedings but the statements on which they draw remain confidential. Witnesses may therefore safely cooperate with the investigators in the knowledge that they will not be incriminating themselves or, even if they are not culpable, providing ammunition for opportunist civil legal actions in negligence.

These protections are constantly under threat by the need to attribute blame. Why do we investigate accidents: to prevent them recurring or to identify and punish the guilty?

Conclusion: Impartial, non-judgemental investigation has proved invaluable for transport safety and needs to be generalised to all complex system failures.

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Acknowledgements

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Revisiting the causes of the Hatfield Rail Crash

By Prof Roger Kemp MBE FREng

Executive summary: In October 2000, an InterCity 225 train derailed south of Hatfield station, resulting in four fatalities and more than 70 people injured. The official inquiry blamed failures of the maintenance contractor and poor supervision by the infrastructure manager. Viewing the accident as the outcome of a failure of a complex system suggests that much of the blame rested with the governance arrangements created by the privatisation of the rail network.

Tags: transport, train derailment, train accident, business restructuring, privatisation, East Coast Main Line (ECML), qualitative analysis, complexity, budget commitments, United Kingdom

Section 1: Background and introduction

The accident

On 17 October 2000, an InterCity 225 train (IC225) bound for Leeds left London King's Cross at midday and was travelling north on the East Coast Main Line at 185 km/h when it derailed south of Hatfield station. The train travelled a further 1 km after derailment. The leading Class 91 locomotive and the first two coaches remained on the track. The rest of the coaches were derailed. The buffet car hit two overhead line structures after derailing, resulting in severe damage to the vehicle and the death of four people. In total, more than 70 people were injured, several seriously.

The case study

A model for complex systems failure produced by York University, as part of the Safer Complex Systems project[1], identified two main processes for reducing risk: design-time controls and operation-time controls. It is clear from reading its 2006 report that the official inquiry concentrated on the operation-time controls – in particular the performance and supervision of the maintenance contractor. In the 250-page document, there was almost no reference to how the railway had arrived at a situation where normal operation resulted in a hazardous situation.

This case study discusses how the inadequacy of design-time controls and a consistent and knowledgeable governance structure contributed to regular rail cracking in service. This is a complicated situation that involves both the dynamics and metallurgy of the wheel-rail interface and the politics and governance of the national infrastructure. An appendix provides more detail on technical issues.

The official inquiry

The Inquiry[2] concluded that "The immediate cause of the derailment of the Great North Eastern Railway express passenger train on 17 October 2000 was the fracture and subsequent fragmentation of the [outer] rail on the [northbound] fast line at the Welham Green curve. The rail failure was due to the presence of multiple and pre-existing fatigue cracks in the rail." The underlying causes identified by the HSE (Health and Safety Executive) investigation were that the maintenance contractor at the time, Balfour Beatty Rail Maintenance Ltd (BBRML), failed to manage effectively the inspection and maintenance of the rail at the site of the accident. The investigation also found that Railtrack PLC, the infrastructure controller at the time, failed to manage effectively the work of BBRML.

A preliminary investigation found that the rail had fragmented as trains passed and that the likely cause was rolling contact fatigue (RCF). Repeated high loading caused fatigue cracks to grow. When they reached a critical size, the rail failed. Portions of the failed track at Hatfield were reassembled and numerous fatigue cracks were identified.

The problem of RCF was known about before the accident. It had been studied in the British Rail's Railway Technical Centre during the 1970s and the Inquiry was shown a December 1999 letter warning that the existing Railtrack Line Specification was insufficient to guard against this type of fatigue[3].

Since privatisation, Railtrack had divested much of BR's engineering knowledge to contractors. "The Investigation revealed possible training deficiencies for some of the Railtrack staff involved in the auditing process. Railtrack's LNEZ Compliance and Engineering Manager, in interview, said he was unable to follow discussions of track work at Hitchin because of its technical nature. The Zone Quality Standards Manager stated in an interview: "I do not have knowledge of railway engineering nor railway safety". The job description for the Zone Quality Standards Manager requires 'excellent knowledge of railway engineering safety and contractual matters'.[4]

The effect on Railtrack

As a result of the accident, Railtrack suffered a major loss of reputation and shareholder confidence and was declared bankrupt. The infrastructure, along with its assets and liabilities, was taken over by Network Rail, a government-owned company.

In 2003, five managers and two companies – Network Rail (as successors of Railtrack) and the division of Balfour Beatty that maintained the track – were charged with manslaughter and breach of health and safety regulations in connection with the accident. The trial began in January 2005. In July, Balfour Beatty changed its plea to guilty on the health and safety charges and, on 6 September, Network Rail was found guilty of breaching health and safety law. All of the manslaughter charges against the executives were dismissed by the judge.[5]

Section 2: Analysis and insights

Why was the rail prone to RCF?

The wheel-rail interface is an area that has, over the years, been subject to many debates between train designers, operators and infrastructure managers. It is a complex technical area and the specification of the interface involves many compromises. (See appendix for details)

Rolling contact fatigue (RCF) is triggered by a combination of contact pressure between the wheel and the rail, the longitudinal forces between the wheel and the rail surface and the number of wheels passing the site.

Contact pressure is the weight on the wheel divided by the contact area. The latter is influenced by the wheel diameter and by how well the wheel profile is matched to the rail profile. Longitudinal force is determined by the levels of acceleration and braking, but also by suspension characteristics.

It can be seen from the appendix that the factors that influenced RCF were decided on the basis of disconnected criteria – some to reduce risk in other areas; some to keep down costs; and some to improve access for wheelchairs. Decisions were taken (or, at least, strongly influenced) by infrastructure managers, train operators and designers, safety authorities, pressure groups and the overriding government limit on costs. RCF was not specifically considered but was an outcome – a so-called emergent property.

How did this situation come about?

Privatisation

During the second world war, the British government took a management role in many key industries and the aftermath of the war saw the traditional balance between capital and labour shifted in favour of the latter.[6] The Conservative Government, elected in 1979, had an ideological commitment to reducing the power of the trade unions, shrinking the role of the state and 'correcting' the balance between capital and labour. Privatisation of nationalised industries contributed to these aims and, over the next 18 years, the national aerospace, electricity, oil, gas, coal, water, telecomms, council housing, buses and many other industries were sold.

The UK rail industry was privatised over a period, from 1984 to 1997. Initially ancillary businesses (hotels, ferries, etc) were sold, followed in 1989 by British Rail Engineering (the train building activity); then restructuring was implemented to establish strict *commercial* relationships between the different 'shadow franchises', infrastructure units and suppliers. In 1994, the railway infrastructure was transferred to Railtrack. This complied with the EU directive to separate infrastructure from operations, but went much further than in other member states. Finally, rolling stock and other assets were transferred to several dozen private sector businesses.

The assumption was that safety of the network would be assured by compliance with standards laid down by Railtrack's *Safety and Standards Directorate*. Mandatory standards on, for example, the width of gangways are easily managed by a standards regime. The international airline industry has demonstrated that high levels of safety can be achieved when aircraft, airports and air traffic control are managed by many separate organisations; so separation of ownership is not, per se, hazardous, but how the separation is managed is important. Achieving a good compromise between a dozen difficult-to-calculate parameters cannot be achieved by compliance with commercial standards written by bodies unfamiliar with the technical problems that need to be managed.

To some extent, Railtrack maintenance managers had been put in an impossible situation. The design optimisation work had not been done and the level of maintenance needed was well above that envisaged during the privatisation, or budgeted for with Balfour Beatty. It was obvious that a different strategy was needed, but Railtrack didn't have the financial resources, expert knowledge, access to machinery or the political weight within the industry to undertake a disruptive programme of re-engineering.

It should be noted that Network Rail, the successor of Railtrack, instigated a more intensive rail replacement, reballasting and rail grinding programme than either British Rail or Railtrack had achieved – but this required significant capital investment in plant and machinery and a 200% increase in subsidy. This is shown in **Figure 1**, taken from a 2018 government report.[7]

In retrospect, it is clear that privatisation of the rail infrastructure was based on an unrealistic business model that was unable to support the necessary maintenance costs.

Management of the wheel-rail interface

The appendix summarises the complexity of the wheel-rail interface on a railway and the effort that has to go into achieving a compromise between vertical forces, lateral forces, unsprung mass, performance, maintenance costs and all the other factors impacting the infrastucture and vehicles.

The management of bogie stability and the wheel-rail interface had never been particularly good under the British Rail regime and this deteriorated with preparations for privatisation. The strict commercial regime prevented the traditional engineering process of bringing the parties together round a table to decide on how best to resolve interface issues and achieve the 'least bad compromise' between competing objectives. As noted by the Inquiry, privatisation also resulted in responsibilities being allocated to people with no in-depth understanding of the underlying science and engineering.

However, the failure to consider RCF during the design phase cannot wholly be blamed on preparations for privatisation. It was never an issue that appeared in requirement specifications for British Rail locomotives or rolling stock. Probably, this was because it was a complex issue. It was not possible to lay down hard and fast rules in a specification that would 'solve' the problem. As discussed earlier, it was an emergent property that resulted from decisions taken by many different individuals or groups over a long period.

Section 3: Discussion and transferable learnings

The Health and Safety at Work Act and complex projects

The Health and Safety at Work Act 1974 is the primary legislation covering occupational health and safety in Great Britain. It replaced various Factories Acts (since 1833) and the *Offices, Shops and Railways Premises Act 1963*. The legislation was based on the 1972 Robens Report and was focused on factories, offices and other enterprises. Railways and other transport systems were specifically excluded from the report's recommendations.

The Act was designed for a world in which a duty holder could be identified as responsible for an enterprise. It required the duty holder to identify risks and reduce them to As Low As Reasonably Practicable (ALARP).[8] The concept of duty holder works satisfactorily for incidents like the Grayrigg derailment,[9] where investigators quickly came to the conclusion that it was caused by a badly maintained set of points. It works less well when there is not a single

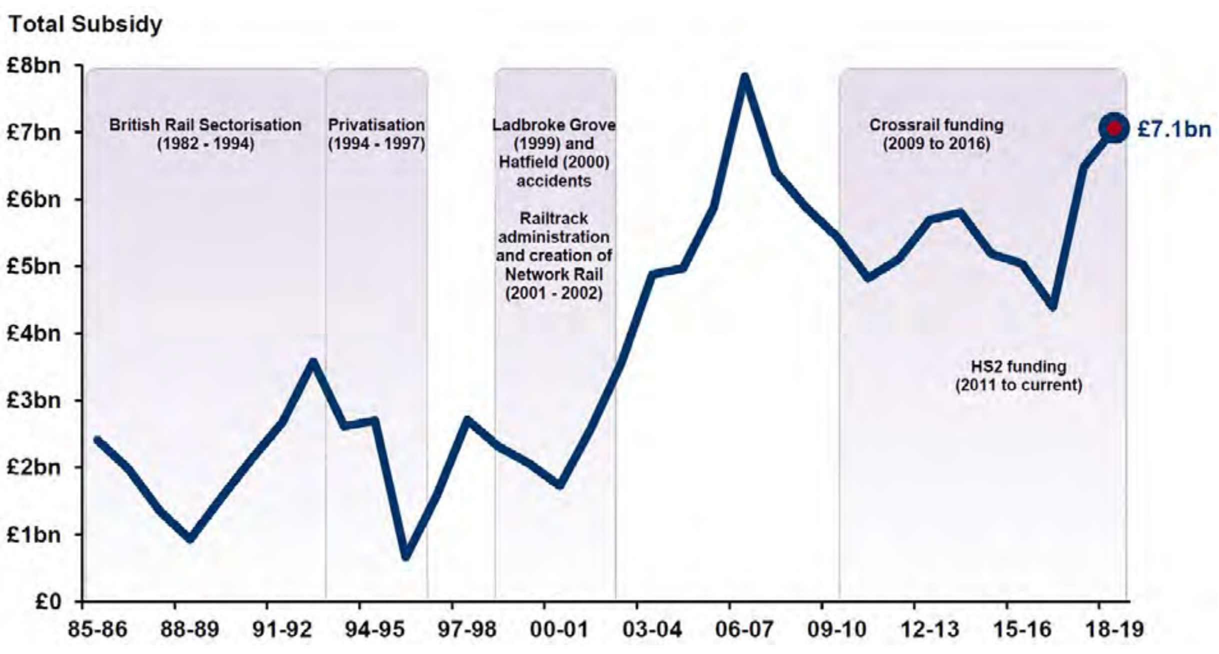

Figure 1: Subsidy to rail industry at 2018 prices.

organisation that can be held responsible. As a recent Lloyds Register Foundation[10] report states: "Many regulatory methods were designed for worlds and risks that can be very different from those faced today. Innovations using technology can now move seamlessly across sector or national boundaries at speeds and scales not previously experienced."

Dividend responsibilities and corporate memory

Under British Rail, responsibilities were split between the engineering and operating departments. In the last resort, the Chairman of the British Rail Board was the person accountable for overall railway safety and for ensuring that adequate precautions had been taken to avoid hazardous emergent properties. All departments of the railway could call on shared expertise on topics like RCF or bogie dynamics in the Railway Technical Centre.

In the privatised railway of the late 1990s,[11] trains were purchased by rolling-stock companies (ROSCOs) and were leased to train operating companies (TOCs) who, after competitive bidding, had been awarded a franchise by the Office of Passenger Rail Franchising (OPRAF), part of the Department for Transport (DfT). TOCs and/or ROSCOs were required to submit a safety case to the safety regulator and/or infrastructure owner (Railtrack) proving that vehicles complied with Railway Group Standards. This responsibility was normally discharged through contracts with suppliers who, in turn, were required to appoint an independent Vehicle Acceptance Body (VAB) to carry out the work. The infrastructure was owned by Railtrack, a private-sector company.

For many aspects, the strands of responsibility for the wheel-rail interface only came together in the DfT. In this structure, there was no single person or organisation accountable for overall railway safety. There was also no shared expertise and no forums where issues, such as managing emergent properties, could be discussed. The Hatfield incident demonstrated the rupture of corporate memory during the privatisation process.

For many years, the HSE has published guidance for company directors on the need to consider health and safety when planning company restructuring.[12,13] If an inquiry determines that a serious accident was, at least partially, the result of inappropriate business re-engineering, legal action might be considered. However, there does not appear to be an equivalent requirement for the restructuring of complete industries by government legislation.

Hatfield – failures of risk management

The introduction refers to a report by York University,[14] which describes a model for the evolution of systemic failures in complex systems, shown in **Figure 2**. The report identified two main processes for reducing the risk: design-time controls and operation-time controls.

Risks propagate through a complex system from causes to consequences to systemic failure. At different stages in the project there are design-time controls and operation-time controls that could reduce the risk. Effective design-time controls can reduce the potential consequences of intrinsic risks that are passed through to system operation. Across both phases, York identified three operational layers: governance, management and technical. In each, there could be exacerbating factors making them less able to manage risk.

When analysing the Hatfield crash, it appears that the York model is lacking a stage – the specification. Before there can be design-time controls, the design team needs to know there is a risk that has to be managed. In the procurement of the 1225 trains, RCF was not identified by British Rail as an issue that train designers needed to be involved with. In the frenetic activity to start work on a project that was won on the basis of a best and final competitive bid with a two-year delivery time and stringent penalties, there were no prizes for diverting design effort onto a list of difficult issues that were not in the specification.

The process of design → operation, assumed by the York report, is meaningful for a discrete project.

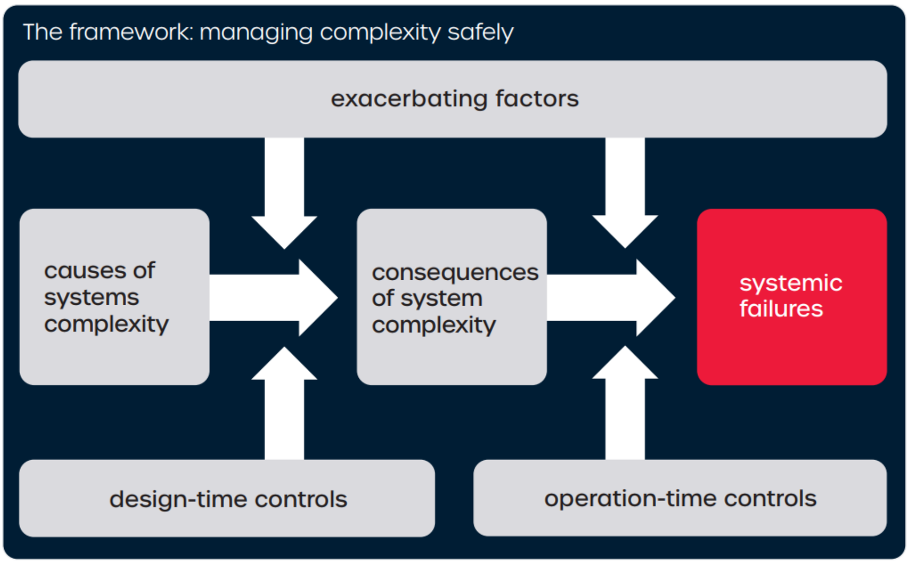

Figure 2: Sources of systemic failures.

It is less useful for managing established infrastructure that has been in continuous use since the mid-19th Century. What was needed, but was lacking, was ongoing technical oversight that kept emergent issues, like RCF, under review and advised on mitigating actions on both sides of the wheel-rail interface. There was no 'through life' governance that tracked, updates and recorded risk profiles through different phases of the evolution of the technology on the network.

The restructuring of the railways in the 1980s was based round a model of independent companies entering into legal contacts with each other where the management layers in the various parties were constrained to work within the Balkanised[15] commercial structure. People in the technical layer were recruited to ensure compliance with specifications, rather than to understand the science behind the systems they were working on. This was particularly true for the VABs which had a 'tick box' culture. As has been found in other investigations, such as that into building fire standards,[16] compliance with standards/ specifications does not necessarily mean something is safe (especially when those checking compliance do not adequately understand the principles behind the standards).

The failure of design-time controls was primarily an issue of governance. The industry was restructured in a way that did not allow interface problems to be adequately resolved during the specification and design phases and thus contributed to a complex system prone to a type of fatigue fracture that could have serious consequences and that placed high demands on the operation-time controls.

A new model of risk management

The 1974 Health and Safety at WorkAct worked well for the stable, self-contained, hierarchical manufacturing companies and similar organisations for which it was originally designed. However, triggered by the reforms of the 1979-1990 governments, the scope and structure of businesses are now radically different. Many public services have been privatised. Industries in both the public and private sectors have been disaggregated so a service or product is delivered by several organisations which may, or may not, have 'joint and several'[17] obligations to maintain a safe service. New funding models, such as special-purpose vehicles, private finance and debt financing, along with multiple layers of subcontracting and a wider use of consultants, have further diluted the sense that a named individual or board of directors is ultimately responsible for a project's safety performance.

Professor James Reason[18] proposed a Swiss cheese model of risk where different layers individually offered incomplete protection against catastrophe but, between them, they prevented hazards turning into disasters. In the current environment, one could consider that the layers include:

- An organisational layer, including a safety management organisation;
- A design and development layer;
- A process layer, including design reviews and safety audits;
- A skills and experience layer, and
- A culture layer.

Each of these layers could provide an impediment to a hazard from turning into a crisis. However, they all rely, to a greater or lesser extent, on the organisation having the appropriate structure and people. If, for example, a railway organisation does not have people with experience of how a railway operates – and how it can fail – it is unlikely that an appropriate safety management system will emerge. The situation prior to the Hatfield crash appeared to be that RCF mitigation in the design phase was largely ignored and safety relied on the single layer of inspection and maintenance.

Living with technology

Earlier sections of this case study, and particularly the appendix, illustrate some of the technical complexity of the wheel-rail interface, the factors that contributed to the growth of RCF and the failure to suppress it. This was partly because the politicians, civil servants and managers setting up the governance and management layers did not understand the RCF process or the risks that could be entailed by failure to manage it. This is hardly surprising – it is a difficult subject that, to understand adequately, requires a level of 'nerdy'[19] understanding not found in most railway managers, let alone in policy generalists.

This is not a problem unique to the rail industry. The National Transportation Safety Board (NTSB) report into the accident on 18 March 2018 – when an autonomous Uber test vehicle struck Elaine Herzberg as she was walking her bicycle across the street in Tempe Arizona – indicates the complexity and in-built assumptions of the automatic decision-making that went into the process of discriminating between a pedestrian, a cyclist and street furniture.

On a related topic, in a 2018 interview with The Guardian,[20] Alison Saunders, the retiring head of the Crown Prosecution Service (CPS), said that Britain's criminal justice system was "creaking" and unable to cope with the huge amounts of data being generated by technology. She said the CPS and police were failing to investigate thousands of cases efficiently – from rape to fraud to modern slavery – and were critically short of the skills and resources required to combat crime.

What general lessons can be drawn from this incident?

This case study has identified three fundamental issues that contributed to the crash at Hatfield:

1. When starting a completely new enterprise using new and potentially hazardous technologies, it is accepted practice to undertake a detailed risk assessment, HAZOP and/or similar processes. In established industries where developments progress slowly, over decades, there tends to be an assumption that the system is fundamentally safe and that each change merely requires a quick check that it does not exacerbate known risks. This is what Sidney Dekker refers to as 'Drift into Failure'[21] (discussed in the appendix).
2. Complex systems have emergent properties that create risk in the system. These can be the result of decisions taken by many different organisations, with no formal relationships. The emergent properties can override layers of safety management that are probably taken for granted, thus placing much greater responsibility on the maintenance processes.
3. Business re-engineering, as a result of takeovers, outsourcing, disaggregation or privatisation can result in a situation where no individual or organisation is responsible for taking a global view of safety. A lesson from this incident might be that, before implementing a major restructuring – such as privatisation or a merger of a safety-related industry or company – those responsible should be required to undertake 'safety due diligence' to investigate how the responsibility for safety would be transferred and to whom as well as the new organisation's vulnerabilities and how these might be affected by the proposed changes. For a large organisation, this could be of equivalent scale to a safety case for a new activity.

An important conclusion of this case study is that the governance, safety audit and regulatory arrangements for complex systems need to evolve at least as quickly as the systems being governed. Procedures originally conceived for regulating self-contained industrial activities with a clear hierarchical management structure may not be appropriate for regulating complex systems with responsibilities spread between many different entities.

Appendix – technical issues

The IC225 train consisted of a Class 91 power car (at the north end) and a set of nine Mark 4 coaches comprising six standard class coaches, a buffet car, two first class coaches and a driving van trailer (at the south end). The train had been specified to have a single power car to reduce costs and also comply with a safety ruling on electrical power transmission between vehicles.[22]

Train dynamics

The dynamic model of a railway vehicle, developed by the Railway Technical Centre (RTC) in Derby, was used by GEC Transportation Projects in the design of the Class 91 locomotive that was involved in the accident.[23] There was a wide variety of train types using the line through Hatfield and most of the design teams for newer models would have followed a similar process.

The Class 91 primary suspension system (between the wheelsets and the bogie frame), shown in **Figure 3**, used coil springs to provide vertical stiffness and rolling rubber ring units to give the necessary lateral and longitudinal restraint.

The means of primary longitudinal restraint is important in understanding the causes of RCF. When a train goes round a curve, the wheelsets attempt to align radially – that is to say the axles point towards the centre of the curve. If the longitudinal suspension is too stiff, the axles remain almost parallel and impose significant longitudinal forces on the rail at the contact with the wheel.

Conicity and bogie stability

On a road vehicle, driven axles are equipped with a differential so that, when going round a curve, the outer wheel can run faster than the inner wheel. On railway vehicles the wheels are linked by a solid axle, but can have different rolling diameters. This is shown, greatly

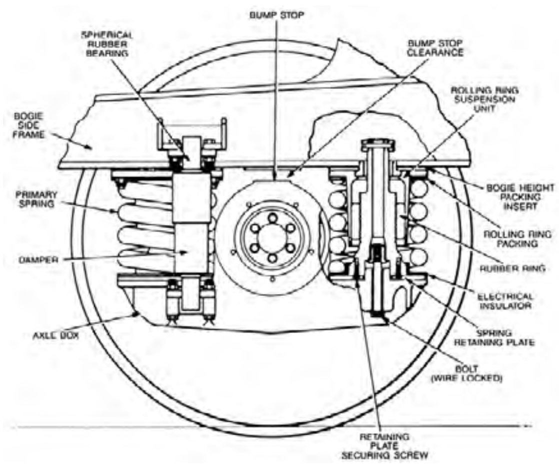

Figure 3: Class 91 primary suspension.

simplified and exaggerated, in **Figure 4**.

The wheel treads are to a first approximation, conical. On straight track, the wheels are central on the track, as shown. On a curve, the wheelset (the pair of wheels and the axle) moves outwards, away from the centre of the curve, so the outer wheel runs on a larger diameter and the inner wheel on a smaller diameter. Obviously, this only works on relatively gentle curves – on sharper curves the wheelset moves to the end of the conical section where there is a flange to prevent it moving further. It is usual to provide flange lubricators, either on the train or the trackside, that apply grease to the flange to prevent excessive wear.

The greater the conicity, the sharper the curve that can be traversed without flange contact and also the greater the centring force applied to the wheelset on straight track. If the centring force is too great and changes too rapidly for a small displacement, the bogie can 'hunt' (oscillate around its central pivot), noticeable by violent shuddering in the passenger vehicle. As a wheel wears, the effective conicity changes.

One of the factors driving up conicity on the Railtrack network was the insistence by infrastructure managers that they should be able to minimise rail replacement costs by transposing left and right rails. If the inside edge of each rail has worn down, by transposing them, the lightly-worn outside edge can be used. Unfortunately, contact between the sharp corner of the rail and the wheel profile created a very high effective conicity. Inevitably, this required high levels of damping in the suspension components. The Class 91 locomotive involved in the Hatfield crash was specified for wheel-rail conicities up to 0.4. In comparison, the French TGV-PSE, its near contemporary, was optimised for a 0.05 conical wheel profile, although it was stable at higher levels.

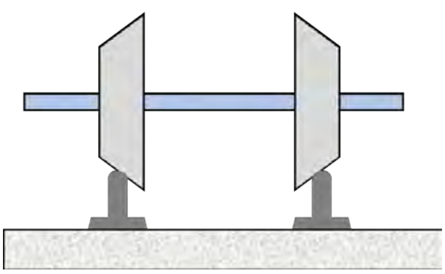

Figure 4: Illustration of conicity.

To avoid flange wear, railways apply lubricant to the flanges on the approach to curves. This can be by 'greasers' mounted on the sleepers that apply grease to passing wheel flanges or high-pressure lubricant sprays mounted on the bogie or stick lubricators (looking like oversize lipsticks) that bear on the wheel flanges. The British Rail privatisation raised several questions about responsibility for maintaining adequate flange lubrication – was it the train operator or the infrastructure owner? Too little lubrication results in flange wear and, in extremis, flange climbing and derailment; too much can contaminate the rail surface and extend braking distances, resulting in signals passed at danger (SPADs) and, potentially, accidents. Following the accident, it emerged that a large proportion of flange lubricators were not working, thus increasing the traction coefficient (see **Figure 6**).

Vertical forces and impact loading

On perfectly smooth track, vertical forces are determined by the axleload. However, real track is not perfectly smooth. Where lengths of track are welded together the weld can be harder than the base metal, so it wears less and, over time, the wheel sees it as a step up, followed by a drop back to the worn surface. There is a similar transient force seen when the wheelset traverses a dipped rail joint. This has long been seen as a problem – a pragmatic comparison of which locomotive types caused track damage (the 160 km/h electric Class 86, with 5 tonne unsprung mass) and which didn't the 160 km/h diesel-powered Deltic locomotives, with a 3.3 tonne unsprung mass). This resulted in the Deltic Criterion against which designs were assessed (**Figure 5**).

Rolling-contact fatigue – an emergent property

Both the conicity/stability criterion and the unsprung mass criterion were 'single input – single output' problems:

- Increase the conicity too much and the bogie goes unstable;
- Too high an unsprung mass causes track damage.

By comparison, rolling-contact fatigue (RCF) is an emergent property. It is caused by the coincidence of three key factors, each influenced by several parameters:

- Susceptible metallurgical properties in the rail;
- High contact stresses;
- High horizontal (particularly longitudinal) forces on the rail surface.

Rail steels are heat treated and quenched. This means that the outer layer of the rail cools and hardens, while the core is still hot. The core then slowly cools and attempts to shrink, thus leaving the outer layer of the rail in compression and the inner core in tension. For this reason, when a crack develops, it first progresses slowly through the outer layer and, when it reaches the core, changes direction and moves relatively quickly through the core, leading to a complete fracture.

A 1991 paper by Cambridge academics[24] provided a summary diagram of the factors that contribute to rolling contact fatigue in railway rails (**Figure 6** is a simplified version). While the

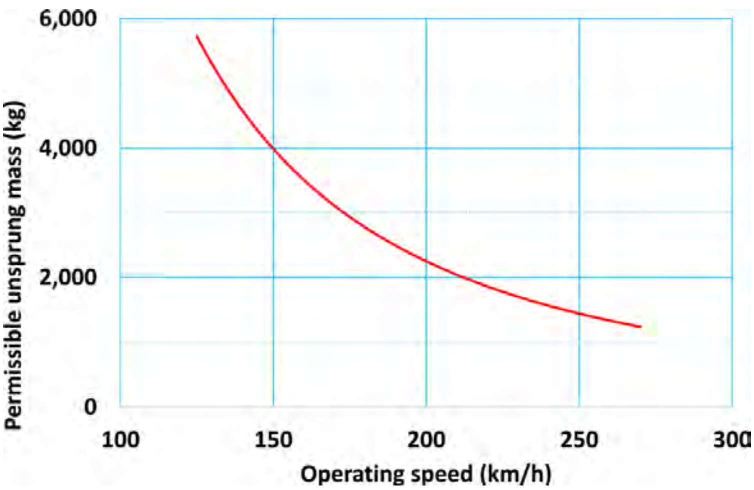

Figure 5: The Deltic criterion.

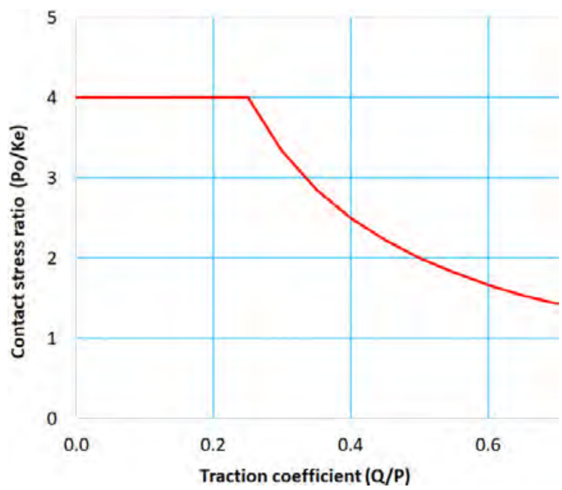

Figure 6: Susceptibility of rails to RCF.

operating point is in the elastic region, the rail surface flexes, but goes back to normal; if it is in one of the flow regions, it distorts permanently and, over time, can crack.

The two axes on the diagram are contact stress (P_o/K_e) and traction coefficient (Q/P). The four parameters are:

P_o – Contact pressure between wheel and rail

K_e – Yield stress of the rail material

Q – Horizontal traction force on the rail

P – Vertical wheel load

Contact pressure (P_o) is influenced by the wheel diameter, axleload, wheel/rail profile mismatch, track smoothness and cornering speeds. For passenger rolling stock, there was pressure to minimise wheel diameters to allow lower floors and ease wheelchair access. Reducing axleload (P) requires either more, but shorter, vehicles or advanced construction techniques using light alloys, rather than steel; both add cost.

Evolution of rail vehicle design

The way in which primary yaw stiffness and axle loads have evolved over the years is indicated in **Table 1**. (It must be stressed, these are particular examples of comparable passenger vehicles; not all vehicle types showed equivalent trends.)

The Mark 3 coach was the standard 125 mph British Rail coach from the mid-1970s, used, electrically-hauled by the Class 87 and Class 90 locomotives, on the West Coast Main Line and in the diesel-hauled HST (IC125). The Mark 4 coach was the 140 mph 1990s design used on the IC225. The Class 319 was designed in the mid-1980s as dual-voltage multiple units running under London from Bedford to Brighton. The Class 175 Coradia were diesel multiple units, originally running in North Wales and North West England. In both examples, it can be seen that the primary yaw stiffness has more than doubled and axleload has increased a little.

The other area where vehicles have evolved is in the tractive effort produced by a locomotive. Each of the Class 43 power cars, at either end of a 1970s IC125 train, produces 80 kN. The single Class 91 power car at the north end of an IC225 can produce 190 kN – more than twice the tractive effort.

Both passenger vehicles and locomotives had evolved to meet the commercial demands of the industry, but there appears to have been no recognition of the effect this evolution could have had on rolling contact fatigue. For an insight into this, it is interesting to consider how rolling stock on that route developed:

- Express steam locomotives, prior to 1961, had (by modern standards) very large wheels, so the contact stress was low. Coaches were wood bodied with low axleloads.
- The next generation consisted of Class 55 Deltic locomotives hauling Mk 1 or Mk 2 coaches. The Class 55 used two Deltic[26] engines, each rated at 1,230 kW. On a six-axle

Vehicle	Primary yaw stiffness (MNm/rad)	Axle load (kN)
Mk 3 coach	17	100
Mk 4 coach	41	115
Class 319	13	150
Class 175	49	155

Table 1: Evolution of bogie characteristics[25]

locomotive, this represented around 300 kW/axle, by the time train heating and auxiliaries had been taken into account.

- From 1978, Deltics were replaced by the 200 km/h High Speed Trains (HSTs), also called IC125. The 4-axle, 70-tonne Class 43 power cars produced 1,320 kW at the rail, or 330 kW/axle.
- Then, from the late 1980s, the IC125s were replaced by the IC225. The 225 km/h, 80-tonne Class 91 power cars produced 1,200 kW per axle.

It can be seen how the speed, weight, power and tractive effort of locomotives crept up over a period of 30 years. At the same time, passenger vehicles increased in weight, because of higher safety standards and improved passenger comfort (air conditioning etc) and their bogies, optimised for higher speeds, became stiffer and thus more prone to triggering RCF. This is what Sidney Dekker refers to as a 'Drift into Failure',[27] when a hazardous situation arises gradually as the result of a large number of small changes, none of which, in isolation, justified a safety analysis going back to first principles.

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Conflict of interest statement

Roger Kemp was Engineering Director of GEC Transportation Projects Ltd during the time that the Class 91 locomotive (the motive power of the IC225) was designed, built and commissioned. Following the acquisition of GEC Power Engineering and Metropolitan Cammell (the builder of the Mk4 coaches also involved in the crash) by the French company Alstom, he spent some time in Paris, first as systems Engineering Director and, subsequently, as Project Director for the Eurostar trains. At the time of the Hatfield crash, he was UK Technical and Safety Director for Alstom Transport and, subsequently, represented UK vehicle builders on the (short-lived) Wheel-Rail Interface System Authority (WRISA). From 2003 to 2020, he was a Professorial Fellow in the Engineering Department of Lancaster University.

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A systems approach to reducing train accident risk

By Brian Tomlinson

Executive summary: This case study explains the systems approach taken by Network Rail to achieve a reduction in train accident risk over a five-year period. It identifies the most effective safety risk reduction options using a combination of qualitative and quantitative techniques, shows how data-driven analysis can be used to identify key failure modes and causes, and establishes key performance indicators to monitor safety risk reduction activities.

Tags: railway, train accident, transportation, complex system, failure modes, key performance indicators, passenger and freight networks, safety, risk reduction, United Kingdom

Section 1: Background and introduction

Railways across the world transport large numbers of passengers and quantities of freight over extensive geographic networks. With trains operating at high speeds and having significant mass, any accident can have catastrophic consequences. Over many years, both transformational and incremental steps have been taken to introduce improved safety measures on railways. While rail is now acknowledged to be one of the safest forms of transport, the potential risk of a train accident remains ever present.

A railway is a complex safety critical system comprising many sub-systems, such as trains, track, structures, earthworks, signalling, electrification and level crossings. As with most complex systems, there are many internal and external interdependencies that can affect system performance. Examples of external factors that can impact railways include the weather/temperature and outside parties, such as road vehicle users and adjacent landowners.

The overall safety of the railway as a system is dependent on the infrastructure manager, train operators and station operators: (a) having a detailed understanding of risk; (b) identifying and implementing effective controls; (c) monitoring their effectiveness; and (d) implementing actions as part of a continual improvement cycle. This is illustrated in **Figure 1**.

This case study will explain in practical terms the systems approach taken by Network Rail, the infrastructure manager for most of the main line railways in Great Britain, to achieve a significant reduction in train accident risk over a five-year period, known as Control Period 5 (April 2014 to March 2019). This includes:

- The in-depth analysis undertaken of the sub-system failure modes and causal factors;
- The identification and analysis of an extensive range of risk reduction options; and
- Implementation of those activities that would have the most significant impact on reducing risk within the funding available.

This approach has contributed to Britain's railway being one the safest in Europe.

Section 2: Analysis and insights

Obtaining a deeper understanding of risk

An accident involving the derailment of a train or collision with another train or object can have very serious consequences, potentially resulting in multiple

Figure 1. Fundamental principles of Network Rail's Health & Safety Management System.

fatalities and injuries and/or the release of dangerous goods being transported. There are many precursor events that could result in a train accident. Within the rail industry, the extent of these are known and include events such as Signals Passed At Danger (SPADs), broken rails and objects on the line. **Figure 2** shows the nine main precursor event groups that comprise train accident risk. It also expands upon one of these groups, the track system, to provide examples of potential failure modes.

As well as the immediate cause, accidents often have several causal and contributory factors. Through the thorough application of accident investigation techniques, a deeper understanding of these factors can be obtained. This can be further used to identify common themes and improve the overall understanding of the risks and the implementation/effectiveness of their controls.

At the end of Control Period 4 (March 2014), Network Rail already had an existing portfolio of ongoing workstreams aimed at reducing train accident risk, such as the introduction of new technology and actions to address investigation recommendations. As part of the overall planning process for Control Period 5, the question arose as to which workstreams, either existing or newly proposed, would have the greatest impact on reducing train accident risk within the funding available.

In 2013 and 2014 a series of 'Deep Dive' risk reviews were undertaken by Network Rail, in relation to each of the train accident risk categories, to review the strategies, policies, initiatives, risk exposure, targets and performance; and to develop corresponding improvement plans. In particular, the 'Deep Dive' reviews undertook extensive analysis of data from a wide variety of data sources to identify trends and correlations of failure/event data with attributes such as year/month/day/time, weather/temperature, detection method and asset type/location. The outputs of this analysis were combined with industry risk model data provided by RSSB (a not-for-profit company owned by major industry stakeholders whose core purpose is to actively help the industry work together to drive improvements in the GB rail system) and intelligence from assurance activities and investigation findings to obtain a much deeper understanding of risk associated with each of the precursor events to a train accident. **Figure 3** provides two example outputs from the 'Deep Dive' analysis undertaken at the time.

Within each 'Deep Dive' risk review a high-level narrative PESTLE (Political, Economic, Sociocultural, Technological, Legal and Environmental) analysis was undertaken to obtain a greater understanding of the potential impact on risk due to both internal and external factors. An overall summary of this is provided in Appendix 1. Examples of external factors that can impact safety include changes in the economy,

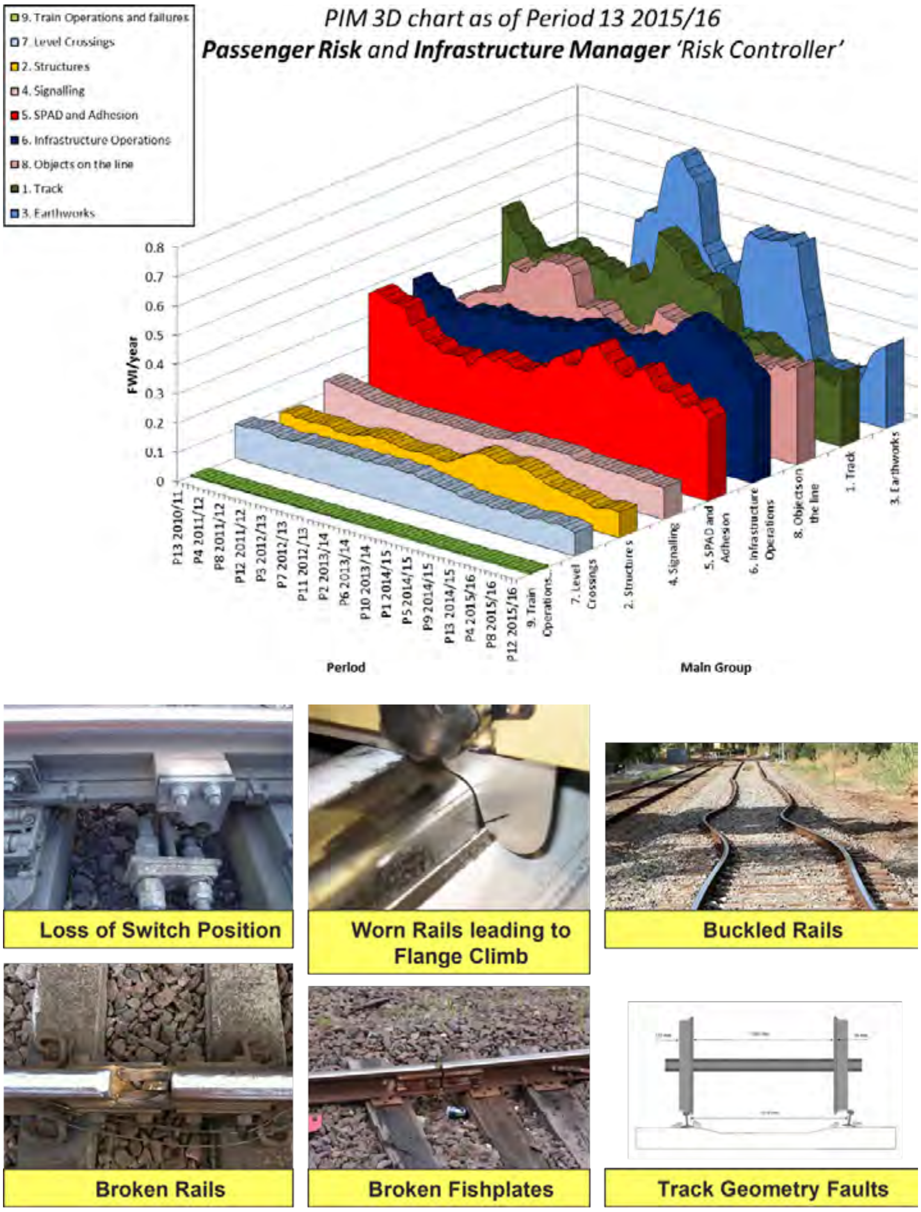

Figure 2. Trend in train accident main precursor event groups (2010 to 2015) and examples of track system failure modes.

funding allocation, security threat level, government, industry structure, new technology, climate change and external risks from other inter-dependent complex systems, such as electricity generation and supply.

Identification and evaluation of risk reduction options

Within railway systems, the risk controls have been established and refined over many years. As a result, nowadays there are fewer opportunities to make transformational improvements to reduce residual risk; although they do exist, for example through the adoption of improved technology and/or more affordable solutions. As there is no dominant category of sub-system risk, the train accident risk reduction strategy needs to be based on the optimum balance of many incremental workstreams/initiatives applied to a wide range of the precursor event types.

In August 2015, following on from the 'Deep Dive' reviews, a significant study was undertaken to identify current and future planned workstreams/initiatives that would, or could, reduce train accident risk. This was conducted in conjunction with the relevant subject matter experts considering: the existing workstreams; expanding/enhancing existing workstreams; or adopting new technology/approaches. The outputs of the rail industry Safety Risk Model (SRM), in conjunction with the analysis of train accident precursor events known as the Precursor Indicator Model (PIM), were used as a basis to identify the relative magnitude and trend in risk of each of the precursor events.

In workshop sessions, subject matter and risk experts used their existing knowledge and the intelligence gained from 'Deep Dive' reviews to estimate the reduction in risk that could potentially be expected if each of the workstreams/initiatives were to be progressed. As part of this exercise their relative effectiveness was considered, taking into consideration the hierarchy of risk controls: eliminate risk; apply engineering control; apply procedural control.

To complete the analysis, each of the identified potential workstreams/initiatives was prioritised by assessing its estimated benefits and costs over a 30-year period considering development, implementation, ongoing costs and associated timescales. The chart in **Figure 4**, shows the output of the cost benefit analysis of more than 70 workstreams/initiatives that were identified. This enabled those initiatives providing the greatest risk reduction to be identified, along with those that had the highest benefit-cost ratio.

Risk reduction plan

The outputs of the 2015 study were used to formulate a train accident risk reduction plan, comprising those workstreams considered to give the optimum risk reduction within the funding available. The plan was initially based on

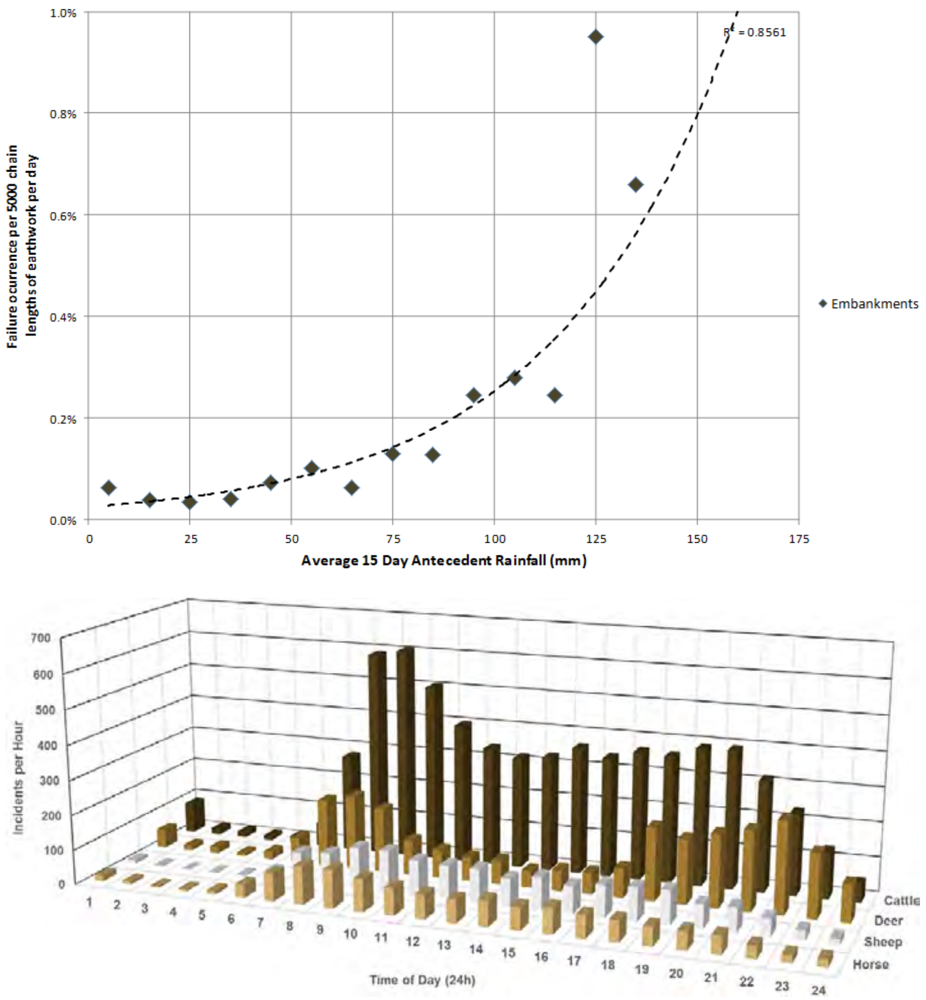

Figure 3. Example outputs of analysis from 'Deep Dive' reviews (correlation of embankment failure rate with 15-day antecedent rainfall, numbers and types of animal reported on the line vs. time of year)

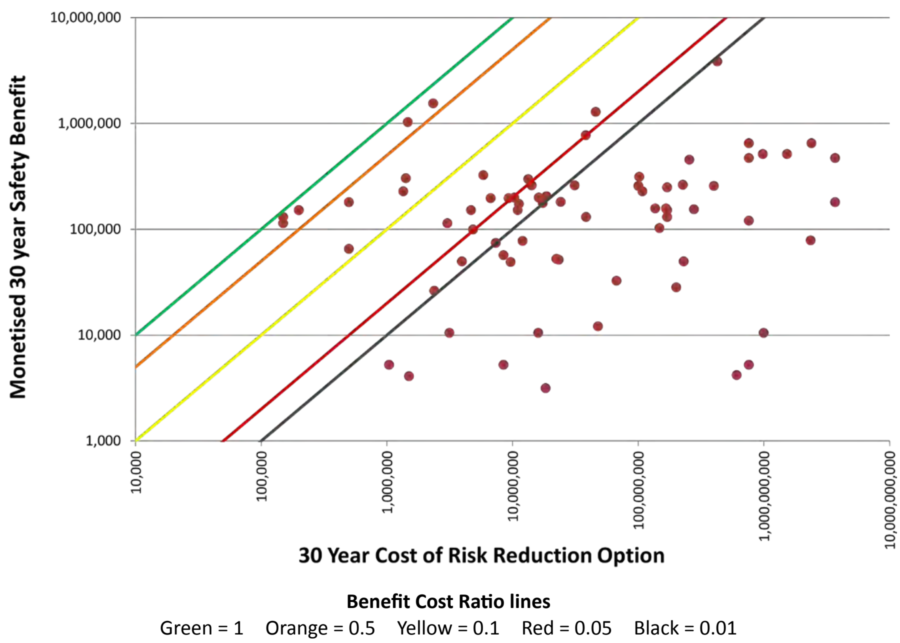

Figure 4. Chart showing the cost benefit of each of the risk reduction workstreams (indicated by the red circles).

a series of activity milestones to record when key stages of the workstreams had been completed or to track the number of risk reduction interventions that have been made. The results of the 'Deep Dives', optioneering study, cost benefit analysis and formulation of the risk reduction plan were all presented to senior stakeholders within the company to obtain their support for the proposals.

Over the following three years, progress against each of the workstreams was tracked through a composite weighted activity (leading) indictor, known as the Train Accident Risk Reduction (TARR) metric, to drive continual improvement year-on-year. The original components of the TARR metric were based on those workstreams considered to provide an improved risk control (such as the introduction of tubular stretcher bars at switches and crossings) or known areas where risk control improvement was required (such as drainage, fencing and vegetation management).

Each year the components of the TARR metric were updated to capture new risk reduction initiatives and, from 2018/19, this included the introduction of Region/Route-specific workstreams more closely focused on key risk areas. The relative weightings of the component workstreams were also reviewed, and adjusted if necessary, following evaluation of actual performance against plan and relative trend in risk (**Figure 5**).

Monitoring performance

Throughout the remainder of Control Period 5, several key performance indicators were closely monitored to assess the impact on train accident risk:

- The performance of the TARR metric itself to measure the achievement of the target volumes and milestones in the risk reduction plan. The metric

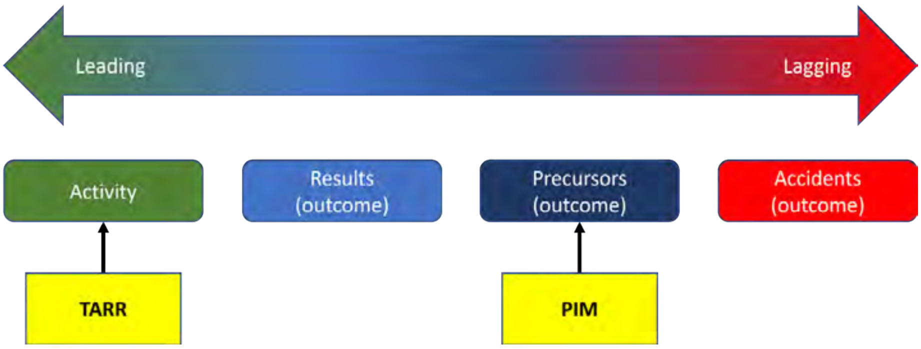

Figure 5. Diagram showing that the Train Accident Risk Reduction (TARR) metric is a leading activity indicator compared to outcome indicators, such as monitoring precursor events or accidents.

attained or exceeded the annual plan in each of the three years after the metric was established;

- The number of failures/events relating to precursor component groups. Improved techniques to visualise this data were applied based on the deeper understanding of risk acquired through the 'Deep Dive' reviews. A good example of this is shown in **Figure 6** with the application of 'control limits' to identify where performance was outside the normal range of variance observed; and
- The Precursor Indicator Model (PIM) performance. The PIM provides a calculation of risk (normalised by the number of train miles) for train accident precursors derived from:
  - The frequency of train accident precursor events that have been reported; and
  - An estimation of their 'average' potential consequences from data contained within the rail industry Safety Risk Model (rather than from the actual consequences of the event itself) or from those events that are risk ranked, such as Signals Passed At Danger (SPADs) and asset failures.

Outcome at the end of Control Period 5

Over the control period, an overall reduction in risk of 37% was achieved against a baseline target of 19%. Each of the targets for the main precursor event groups was also met. This is shown in **Figures 7** and **8**.

While the PIM results showed a significant overall reduction in train accident risk in Control Period 5, more detailed analysis of the model outputs highlighted that trends in some of the train accident precursor events (such as track, earthwork and signalling failures) have more variation as they are more susceptible to the effects of adverse weather and temperature (which can vary in severity from year-to-year). When these precursor trends were analysed over a longer duration, a 31% overall reduction in risk over the control period was calculated. This was still an appreciable reduction in risk compared to the original 19% target.

In terms of absolute risk reduction, the greatest reduction in risk was achieved in the track system, earthworks and objects on the line main precursor event groups. While there was some variable impact on risk due to weather/temperature effects (and other factors both internal and external to the railway system), it was concluded that there was a genuine causal reduction in risk resulting from several of the TARR workstreams. Examples of these include:

- The contribution of the tubular stretcher bar installation programme and improvement in the identification of switch wear towards reducing track system switch and crossing failure risk;
- The contribution of improvements in trainborne monitoring towards reducing track system twist & geometry fault and broken rail risk;
- The impact of increased focus on drainage maintenance on reducing track system and earthwork failure risk;
- The contribution of scour mitigation measures and improvements in competence towards reducing rail bridge failure risk;
- The contribution of level crossing closures and other safety improvements towards reducing level crossing risk; and
- The impact of increased focus on vegetation maintenance on reducing risk due to trees on the line.

While most of the train accident risk precursors showed either a consistent or improving trend, there were a very small number showing a gradual worsening trend within the control period. An example of this was the risk associated with non-rail vehicles on the line, despite implementation of road vehicle incursion mitigation measures being a key TARR volume. This is another example of a risk that can be significantly influenced by external factors.

Section 3: Discussion and transferrable learning

Reflecting on this case study, there were several key factors that needed to be present to successfully achieve the overall outcome objective. These are:

- A risk breakdown structure of the railway system and identification of precursor events based on known and theoretical failure modes;

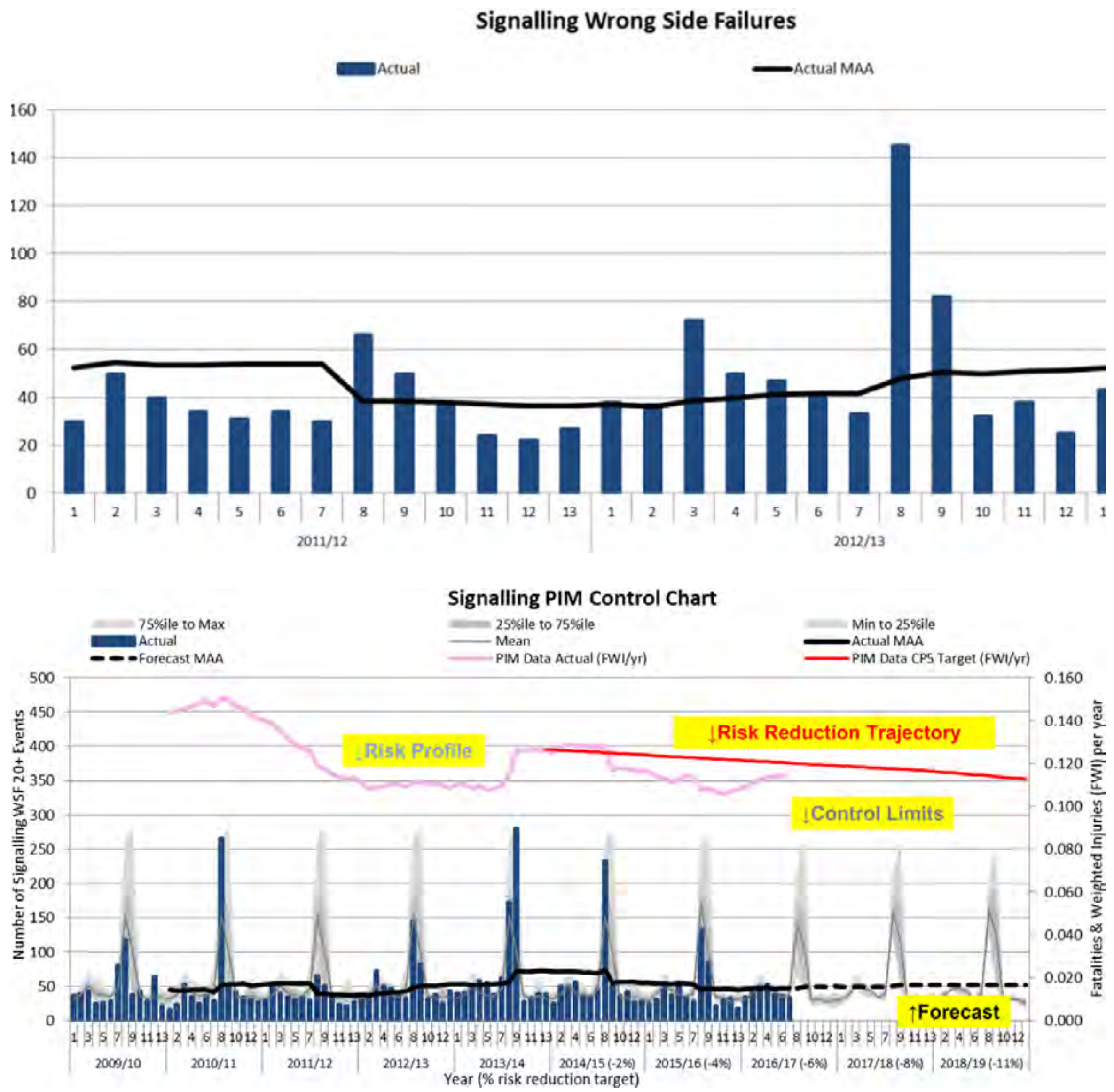

Figure 6. Analysis of signalling wrong side failure data (before 'Deep Dive' on the left, after 'Deep Dive' on the right which includes the risk trajectory and highlights seasonal variation by the application of control limits).

- Availability of relevant failure data and key data attributes, assurance outcomes and investigation findings to enable the 'Deep Dive' analysis to be undertaken;
- The existence of the industry Safety Risk Model containing information on both event frequency and consequence relating to precursor events;
- Access to subject matter experts for each of the engineering and operational failure modes and experts in risk, analysis and systems engineering;
- Estimation of indicative estimates of cost, timescales and benefits associated with each of the risk reduction workstreams/initiatives;
- A good understanding of the impact of both internal and external factors that impact risk;
- Senior level buy-in, leadership, commitment and support throughout;
- Continued performance monitoring through a combination of both lagging and leading key performance indicators;
- Acknowledgment that the strategy needed regular review and refinement; and
- The ability to respond proportionately to events arising without undermining the overall risk reduction strategy.

There are also a few areas where, upon reflection, further improvements and refinements to the methodology applied could be made:

- Further study and analysis of inter-dependencies and commonality between precursor events, including across sub-

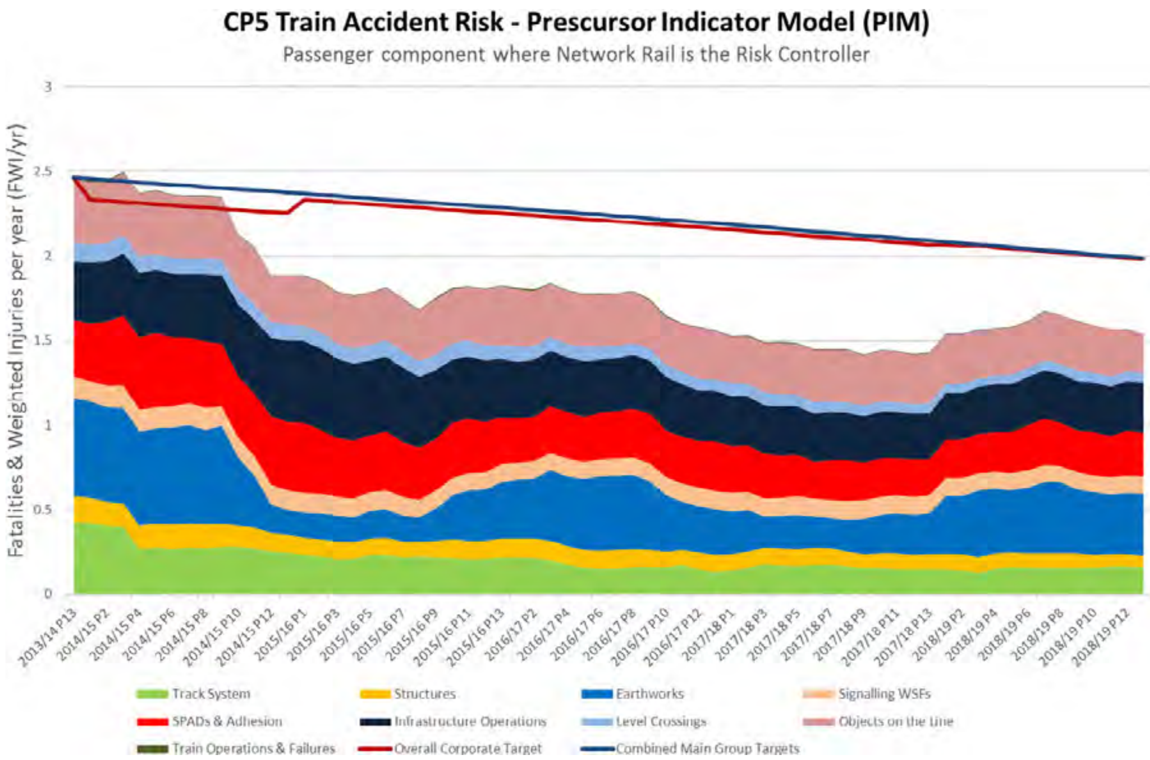

Figure 7. Train accident risk PIM results for Control Period 5.

	Target reduction in risk in CP5 (%)	Actual reduction in risk in CP5 (%)	CP5 Target Met	Proportion of total risk at CP4 exit (%)	Proportion of total risk at CP5 exit (%)
Overall PIM	**19**	**37**	Yes		
Track System	18	62	Yes	17.4	10.5
Structures	29	56	Yes	6.2	4.3
Earthworks	35	37	Yes	23.5	23.7
Signalling WSFs	11	19	Yes	5.1	6.6
SPADs & Adhesion	13	23	Yes	13.6	16.7
Infrastructure Operations	10	15	Yes	14.1	19.2
Level Crossings	28	47	Yes	4.5	3.8
Objects on the Line	7	39	Yes	15.4	15.1
Train Operations & Failures	No target set	59	Not applicable	0.2	0.2

Figure 8. Risk reduction in Control Period 5 for each of the main precursor event groups.

system boundaries and closely involving other industry parties;

- An improved feedback loop between activities undertaken to reduce risk and the potential outcome on accident precursors to identify those that are making the greatest impact and those that are not impacting risk in the manner originally envisaged;
- Provision of improved cost data/estimates and sensitivity analysis, for example three-point estimates; and
- Wider and more detailed consideration of other external factors that could impact risk, such as those identified in the PESTLE analysis (see **Appendix 1**) and the UK Cabinet Office's National Risk Register.

In terms of transferable learning to other sectors and industries, this case study:

- Provides a practical methodology to identify the most significant and cost-effective safety risk reduction options for a complex system, comprising many sub-systems impacted by both internal and external factors, using a combination of qualitative and quantitative techniques;
- Shows how a data-driven approach can be taken to assessing a very complex system to understand its key failure modes and causes, supported by risk modelling and analysis; and
- Identifies how to establish a suite of key performance indicators that monitor activity being undertaken to reduce safety risk. These indicators can then be refined year-on-year to target further improvement in safety performance.

An overall summary of the methodology applied is shown in **Figure 9**.

These techniques could be adopted by any safety critical industry that has established safety reporting processes in place and/or knowledge of system failure modes (actual and envisaged) and their effects. They are simple to understand and apply, which makes them suitable for transferrable application. Also, there is potential for further development and refinement of the methodology applied and to apply it to other system capabilities within an organisation, such as environment, performance, security, etc.

Appendix 1 – PESTLE analysis of factors impacting train accident risk

Political

The main line railway in Great Britain comprises the infrastructure managers (of which Network Rail is the largest), train and freight operating companies and station operators. Changes in government, train operators or wider-industry structure can impact the organisational structure, priorities and funding – which in turn can impact safety. The railway also has a high media profile that can potentially impact decision making.

Economic

Network Rail receives its funding from the Department for Transport in five-year Control Periods. The level of funding impacts the investment in maintaining, renewing and enhancing the infrastructure and the operational running of the railway – this can have a direct impact on safety. Funding, therefore, must be used in the most cost-effective way to achieve the organisation's objectives.

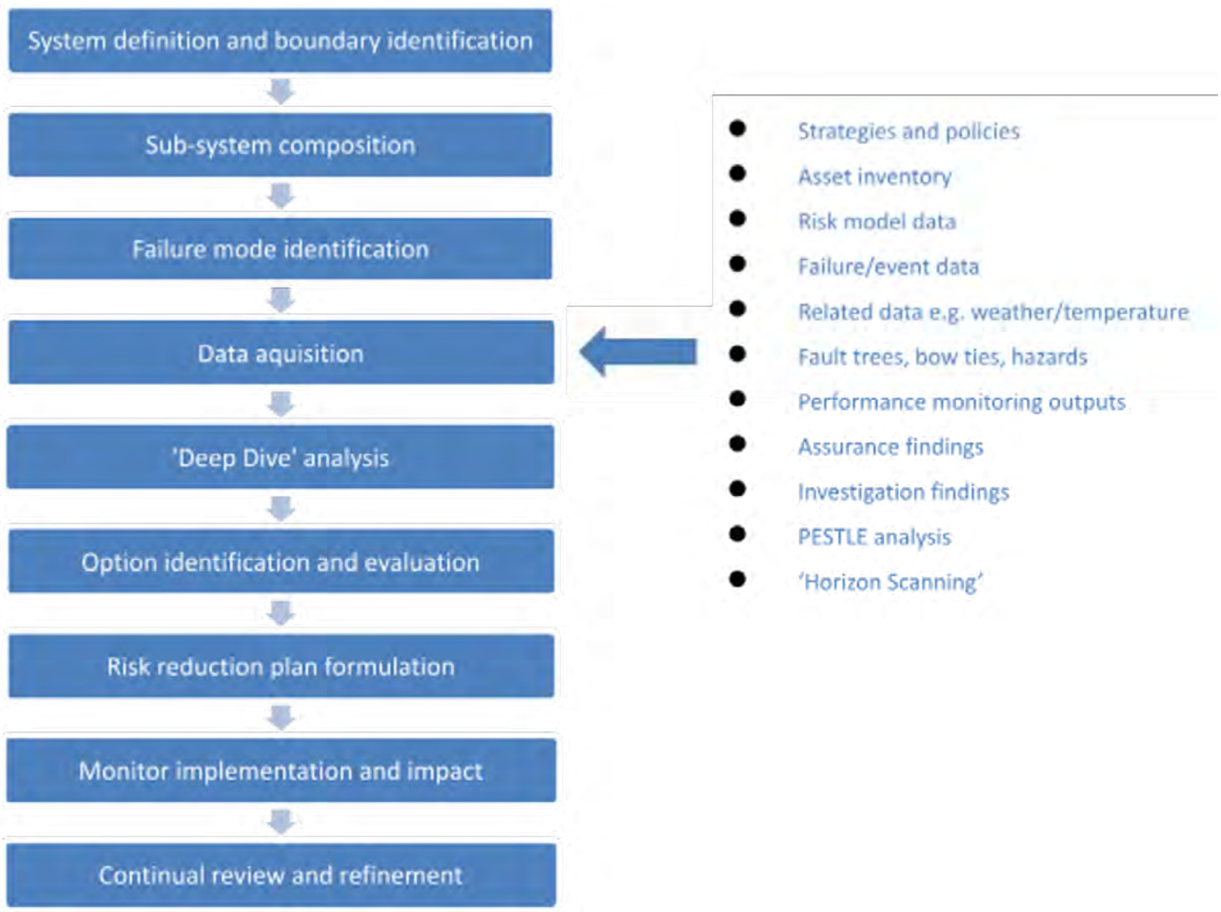

Figure 9. Overview of methodology applied to reducing train accident risk.

Insufficient or inappropriate allocation of funding could result in a deterioration of asset condition.

Sociocultural

The railway is a safety critical system and safety is a strong cultural value held by all people who work for the railway. Passengers and members of the public can each have a different perception of risk and, as such, sometimes do not act safely. An example of this is at level crossings where unsafe behaviour is frequently observed. This is considered when determining the risk controls that need to be applied.

Technological

Technology makes an extremely important contribution towards improving railway safety. Most of the significant reductions in risk that have been achieved over the years have been made through advances in technology. Network Rail has made significant investment in research and development in order to identify and adopt successful new technology to reduce safety risk. One important area is seeking more cost-efficient and reliable engineering solutions. Through greater automation of activities, such as track inspection, the risk of human error and risk to workers can be reduced. Other technological developments include the introduction of new signalling systems, use of drones and intelligent infrastructure monitoring.

Legal

In addition to the general health and safety legislative requirements that apply to the railway, such as the Health & Safety at Work Act, there is also a wealth of railway-related safety legislation. Changes in legislation have a positive impact on safety, underpinned by the use of engineering safety management processes and risk assessment.

Environmental

As the railway largely operates in an external environment, its performance can be impacted by the weather and its effects. Rainfall, snow, high/low temperatures, wind, fog and leaf fall can all affect the safe performance of the railway. Examples include flooding of the line, poor adhesion between train wheels and the rails, objects blown onto the line, buckled rails in hot temperatures and earthwork failures. Climate change will therefore have a key impact on railway safety. In reducing carbon, the railway is moving towards more electric trains and alternative/supplementary means of powering trains, for example using batteries or hydrogen.

Acknowledgements

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Understanding and utilising data for a seasonally agnostic railway

By Dr Brian Haddock, Dr John Beckford

Executive summary: This study considers how the Rail Industry might make better use of data to manage 'seasonal bumps' in performance related to extreme adverse weather events. It explores conventional responses and then proposes a new approach rooted in cybernetic modelling of the data enabling adaptive and preventative actions to be taken. We show how more effective use of data in a coherent whole system model can help identify areas of risk and enable anticipatory, mitigating actions.

Tags: seasonal failure, extreme weather and climate, national railway systems, asset management and performance, cybernetics, artificial intelligence, error prevention, systemic modelling, culture, prediction

Section 1: Background and introduction

Each year with seasonal changes and changing weather patterns, the UK railway experiences 'seasonal bumps' causing delays and cancellations. This research explores systemic interactions and interdependencies arising on the UK railway, embracing the information generation and decision processes that enable weather-related decision making to address those. The objective is:

> *"To deliver a 'seasonally agnostic railway' as a safe, resilient, complex adaptive system".*

The System of Systems under consideration

The principal system is the whole UK operational railway (both below and above the railhead) as shown in **Figure 1**.

Our study focuses on three sub-system elements of this overall cyber-physical system:

- Emergency Weather Action Teleconference (EWAT)
- Weather forecasting
- Asset management data.

The UK Railway follows a system of planning and decision represented in **Figure 2**. Non-weather events are excluded from consideration.

Research synopsis

The research explores the belief that current information systems, sources of data, methods of data collection, reporting models and control methodologies are not fully fit for purpose. The absence of meaningful actionable information arising from these deficiencies exposes the railway to risk of compromise to and failure of journeys.

The aim is to develop knowledge, insights, information systems and operational practices to enable a seasonally agnostic railway. The study for the Safer Complex Systems Research Group, RAE, is being delivered as part of the ongoing SAR Model project considering weather and asset data and forecasting potential.

Research objectives and novelty

The three objectives for this research are to:

- Establish whether the data provided for weather-related planning and operational decision making is sufficient for its intended purpose and to identify any gaps;
- Increase the ability of the railway to adapt in operational and planning decisions, both temporally and spatially, for safe operation reduction in failure risk;
- Increase the availability and appropriateness of asset and weather data to support decision making.

A novel factor is that while data is used to support operational running decisions, it has not previously been brought together in a single cybernetically designed system capable of integrating meteorological, asset and operational data to enable assertions about probable future performance.

Integration of data will enable assertions about future performance and the effect of preventative maintenance interventions.

Context and approach of the research

The project aims to support the Network Rail weather resilience strategy team in developing a transformational approach to

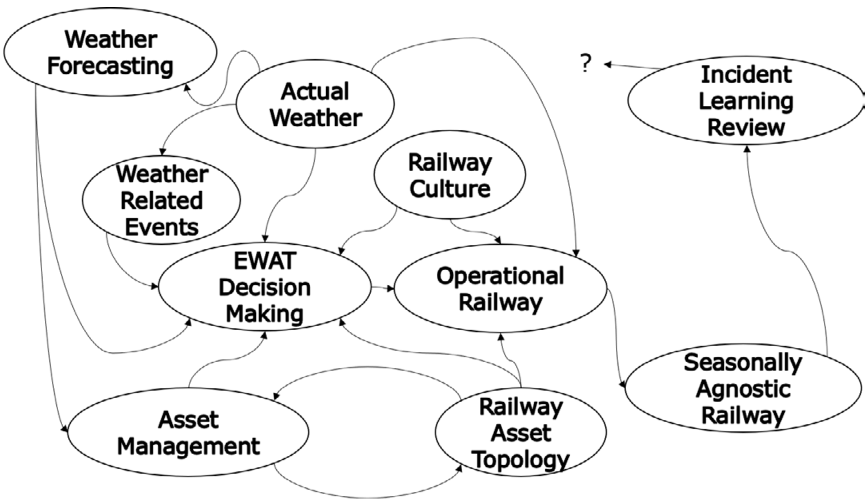

Figure 1: An extreme weather System of Systems

reducing service compromise and failure and fulfil commitments to passengers and freight carriers. The approach will use information about performance to inform both corrective and pre-emptive decision making. This will ultimately embrace all assets (linear and mobile) and entire passenger and freight journeys. The underlying approach adopts cybernetic principles and tools, using information:

- To enable and sustain adaptation;
- To embed lessons learned in the architecture of the railway system;
- To improve reporting systems;
- To enhance maintenance and delivery programmes.

It has been agreed that no work should be undertaken in sustaining weather resilience that is not informative about the state of performance, informed by prior knowledge and connectible to the economic and social outputs required. The outcome, though distanced temporally and spatially, can then be evaluated in context with the aim of generating an increasingly weather resilient railway.

Section 2: Analysis and insights

A notable challenge is that much of the data held by the railway is in unstructured or semi-structured formats.

Extreme weather response

The traditional extreme weather response system used by the railway is an Extreme Weather Action Teleconference (EWAT).

The EWAT process is intended to enable the railway to make short term adaptations to timetables and operating decisions in order to mitigate the effects on the railway and its passengers of extreme

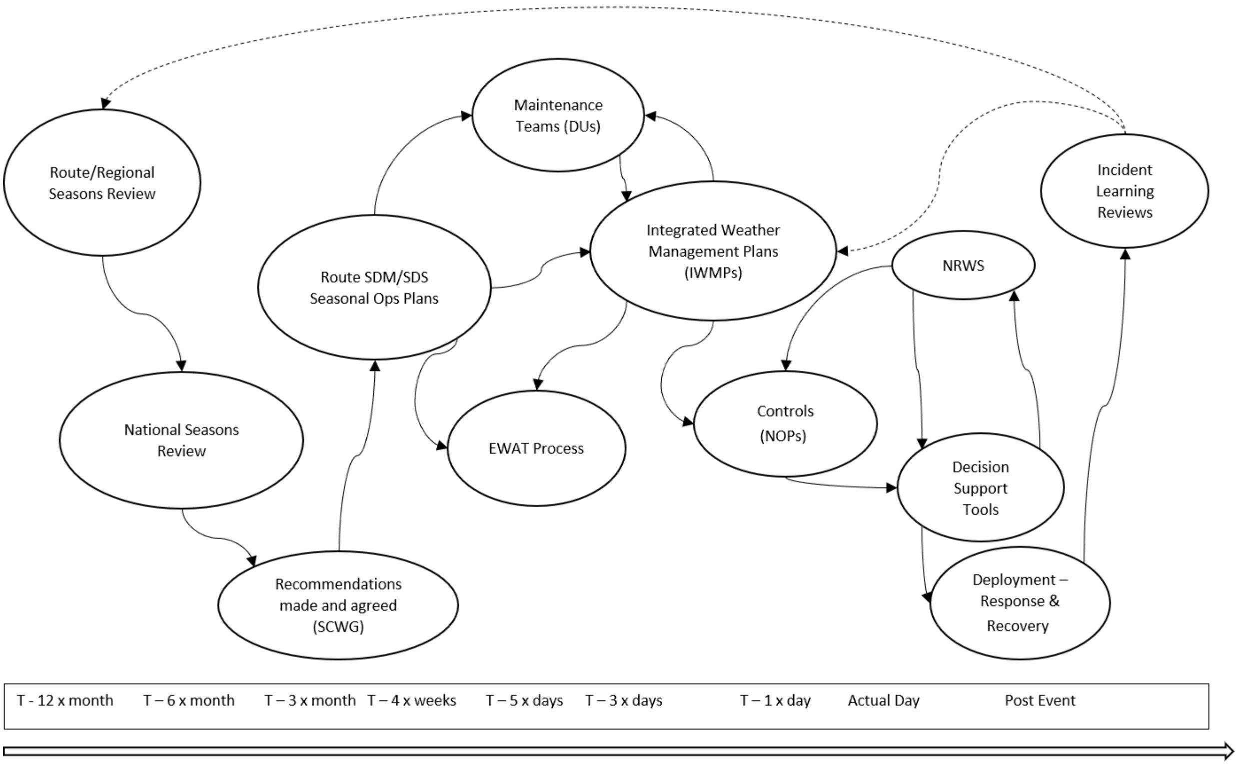

Figure 2: Current system of planning and decision

weather events. Weather forecast providers (MetDesk) deliver two-day to five-day forecasts that underpin the industry response to impending events. The forecast process is as follows:

- Received by email at each control (ROC) nationally;
- Risk assessed by the Route Control Manager (RCM) or equivalent;
- Distributed across the entire region.

Thresholds are in place for each weather parameter that define the risk to the network around four core alert levels of Normal, Aware, Adverse, Extreme. This simple coding of alert status allows the teams within ROCs to expedite a judgement on whether to initiate any actions in accordance with their extreme or adverse weather management plans (E/AWMPs). If an extreme threshold is forecast to be breached, the control team initiates an EWAT, the five-day process following five stages from the initial forecast to the day itself (**Table 1**).

Critique of EWAT

EWATs are considered to provide the principal benefit of reassurance to senior leaders that the forecasted weather has been considered. However:

- Outputs of EWATs do not provide a quantitative summary of the risk exposure or options of train service provision;
- Reduced train service provision not validated against the working timetable is informationally inadequate leading to confusion for the station staff around which services are, or are not, being provided to passengers along with confusion about speeds and cancellations.
- On main lines, with more than two train operators running services over most sections, there is increased potential for conflicting decisions, particularly where freight services are involved;
- There is no informational connection between seasonal planning and the EWAT process;
- EWATs have become institutionalised, perhaps undertaken to demonstrate compliance rather than because they make a difference;
- Information is often unstructured and oral;
- Mitigations proposed are conditional;
- Large numbers of attendees inhibit effective communication.

The Convection Alert Tool (CAT): Review and critique

Since the accident at Carmont, the rail industry has adopted defined sections of permanent way known as Operational Route Sections (ORS) and developed the Convective (Rain Event) Alert Tool to manage the impact of extreme weather. The first permits fine grained weather forecasting as a means of alerting operators? to imminent risk and allows for the imposition of speed reduction to only the affected area. This acts to minimise the overall performance impact for all other services. Moving from a large scale, rail network unaligned five-day forecast updated every twenty-four hours to a forecast alerting tool updated every five minutes over a small, specific geographical area, wholly aligned with the rail network (ORS), is a significant change. Building on the development of the Precipitation Analysis Tool (PAT), developed from the RAIB Class Report on Landslips, 2015, the CAT was its logical extension.

Critique of the implementation of CAT

An 'Earthwork Sprint' Programme set up shortly after the accident at Carmont consisted of three work streams, each led by a discipline

Stage 1	Business as usual	
Stage 2	Awareness	Day one: an RCM will issue the forecast highlighting the potential risk for Day Five (as per Fig 4). Day two: delivery units will be made aware of the alert by the control. Day Five: If the alert status remains extreme, move to the next stage.
Stage 3	Preparation	Day two/three: Teleconference convened and chaired by the RCM; Engage with TOCs and Delivery Units.
Stage 4	Respond	Day four/five: Monitor changing weather and effects in real time, reassess actions and review decisions.
Stage 5	Recover	Day five and after: Develop consensus with other parties on recovery plans. RCM has sole decision authority on the recovery plan.
Stage 6	Review	Identify what went well, or not, identify improvements, promulgate lessons.

Table 1: EWAT process

expert and convened first in September 2020:

- Meteorological information
- Earth work information
- Operations standards and implementation

A solution had to be developed quickly as Network Rail was under pressure to provide a date for the delivery of a tool that would essentially mitigate, or at least reduce the risk, of another 'Carmont' accident. Given that the accident was associated with convective rainfall Network Rail mandated that a tool would be delivered by Easter 2021 in preparation for the summer 2021 convective season.

The decision to 'deliver' the tool by this date essentially meant that there would be no opportunity to stress test the tool through real convective events.

Network Rail brought in a 'Programme Delivery Team' with little knowledge of what had been agreed under the three 'sprint workstreams'. The National Weather Team and MetDesk knew that effective implementation of CAT would take many months of iterative stress testing, with both users and developers using clear criteria. In practice, only one table-top scenario took place with just a single region and while a scope was established:

- No formal research or evaluation methodology was adopted;
- No control measures were used;
- No independent observers were involved.

The Programme Delivery Team focused solely on the delivery of the tool to control staff, defining success as the completion of the functional tool rather than its utility in safer decision making in the longer term.

Following the single trial CAT was rolled out nationally across all ROCs, although experience showed a significant challenge in making the CAT functional in providing a safer railway. Ownership of the ORS information is a concern, as it signifies that the objective of CAT is not understood in its entirety, a particular concern when prior adverse events are considered.

The cultural response to CAT is very interesting and highlights the lack of true engagement in the longer-term use of such tools for learning. Control teams running an operational railway are fully occupied, yet no one was taken out of their daily role to ensure that the tool was understood and no work was undertaken to establish who was accountable for the end-to-end process. The very nature of the original three workstreams in the sprint did not help this situation:

- The meteorological workstream team was regularly asked by the Programme Delivery Team how the process was working within controls and how the deployment of CAT was being received by train drivers.
- The Programme Delivery Team was not part of the original sprint, in fact most of the team did not know of the three original work streams.
- Confusion was caused through the Programme Delivery Team often putting leaders of the original workstreams under pressure to comment on others' subject matter expertise.

This request alone is indicative of an operational function that perceives itself as 'fire fighting'.

Asset Data, Asset Management and the Seasonally Agnostic Railway (SAR) Model

The idea of a seasonally agnostic railway arose from a series of conversations between Dr. Brian Haddock and Dr. John Beckford. Beckford developed with Haddock a shared model of the challenges confronting the railway and an understanding of how those challenges might be addressed to develop a digital model of the railway with simulation, learning and adaptiveness inherent in its design.

The model will provide a series of choices to the railway with regard to the provision of the train service based on the predicted availability of the network reflecting the likely response of every asset to the forecasted event. The product of its calculations is a forecast weather impact on the timetable at different levels of temporal and spatial granularity. The benefit is the ability to inform:

- Passengers of likely impacts before they travel;
- Operators of the impact on their vehicles and crews;
- Asset managers of the assets they must address to anticipate, prevent or mitigate failure risk.

As the accuracy and granularity of weather forecasting develops, an accurate impact profile for each service group can be developed.

The work was informed by several key ideas from quality management (Beckford, 2017) and cybernetics (Beckford 2021):

- A Learning Cycle based on 'Plan, Do, Check, Act';
- The cost of non-conformance;
  - the costs incurred through failure, both to the railway, to its clients and the wider society which is currently measured by the idea of 'delay minutes'
- The value of non-failure;
  - the economic, environmental, social and political benefits gained through success
- A strategy drawing on the ideas of organisational adaptiveness as the key to survival, including engagement and autonomy of the railway community.

A performance model that measured whether the desired outcome was achieved needed to include:

- The expectations of passengers and freight users;
- The expectations of all other stakeholders – operational, organisational, and political;
- The capability of the railway;
    - addressing the ability of the railway to deliver passenger and freight services under a range of conditions;
- The range (and limits to) weather conditions to which being seasonally agnostic applies (which will need consistent supply of relevant weather data to generate the reporting context against which performance can be measured);
- The cost and value of necessary adaptive behaviour;
- The potential of the railway;
    - what constrains performance and how might changing those constraints enable performance to be improved;
- The actual performance;
    - the capture of data necessary to report performance in a form and format suitable for analysis and interrogation at a rate and frequency that would enable pre-emptive and corrective action to be taken at all levels and time scales.

The model also needs data that links current performance with prior preparedness (maintenance) action, that is a need to link the performance of an asset with its maintenance regime. This allows the determination of a connection between asset maintenance and asset availability/reliability of sufficient validity to inform decision making.

This device adopted is a potentiometer reflecting not just what was done, but how what was done compared with what was expected. This provides a measure of the effectiveness of the action and enables comparison of otherwise dissimilar things.

The results are compiled in a data and reporting system that provides a consistent structure and language to inform the development of the model and an objective view of whether:

- Performance is improving or deteriorating;
- Seasonal preparedness activities are delivering the expected benefit.

Critically, the railway will be able to use the model and its contained data to make useful assertions about the future, that is to make assertions about what is likely to happen if no changes are made AND direct attention to the changes most likely to deliver benefit.

For each operational route section there will need to be three interacting homeostats (**Figure 3**):

- Homeostat One: will reflect on the difference between the weather predicted and the weather experienced.
- Homeostat Two: will reflect on the fit between the weather predicted and the specification of the assets to cope with that weather.
- Homeostat Three: will reflect on the preparedness of the assets to deal with the weather as experienced.

Failure of any of the three loops will mean a degraded (amber) or failed (red) performance of the railway. The aim is to be able to anticipate and pre-empt such degradation.

Figure 4 provides an indicative architecture through which information about impacts collected at ORS level can be distributed 'up' to network controllers and managers and 'out or down' to service operators, passengers and freight carriers.

Figure 5 shows how data collected can be aggregated into performance information at every level from the class or type of asset to ORS, the line, the route and the whole railway.

Figure 6, a conceptual model for an asset criticality and vulnerability index, based on prior work of Beckford and Dudley (Beckford 2021), systemically demonstrates how the criticality of each asset varies with the status of each of the other assets on which

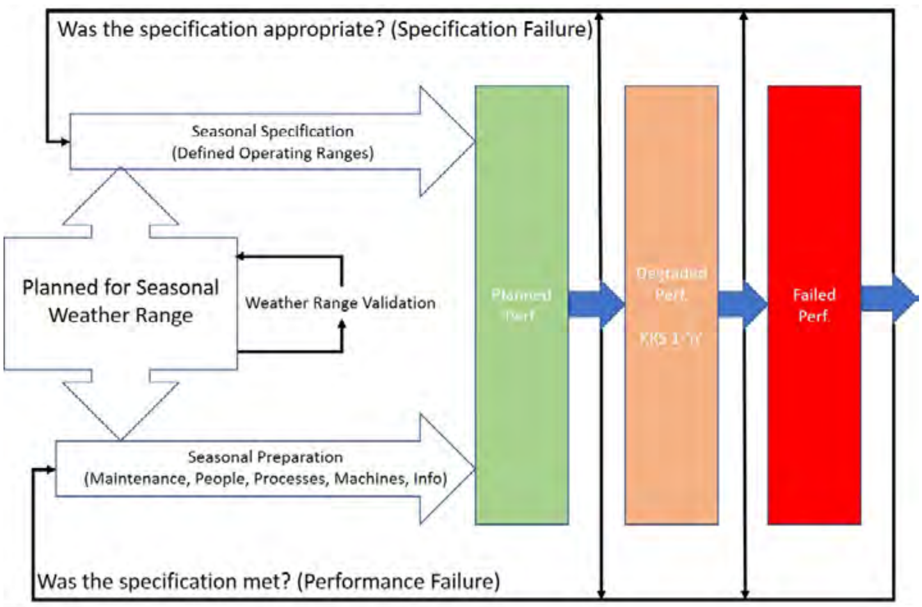

Figure 3: Conceptual Model 1

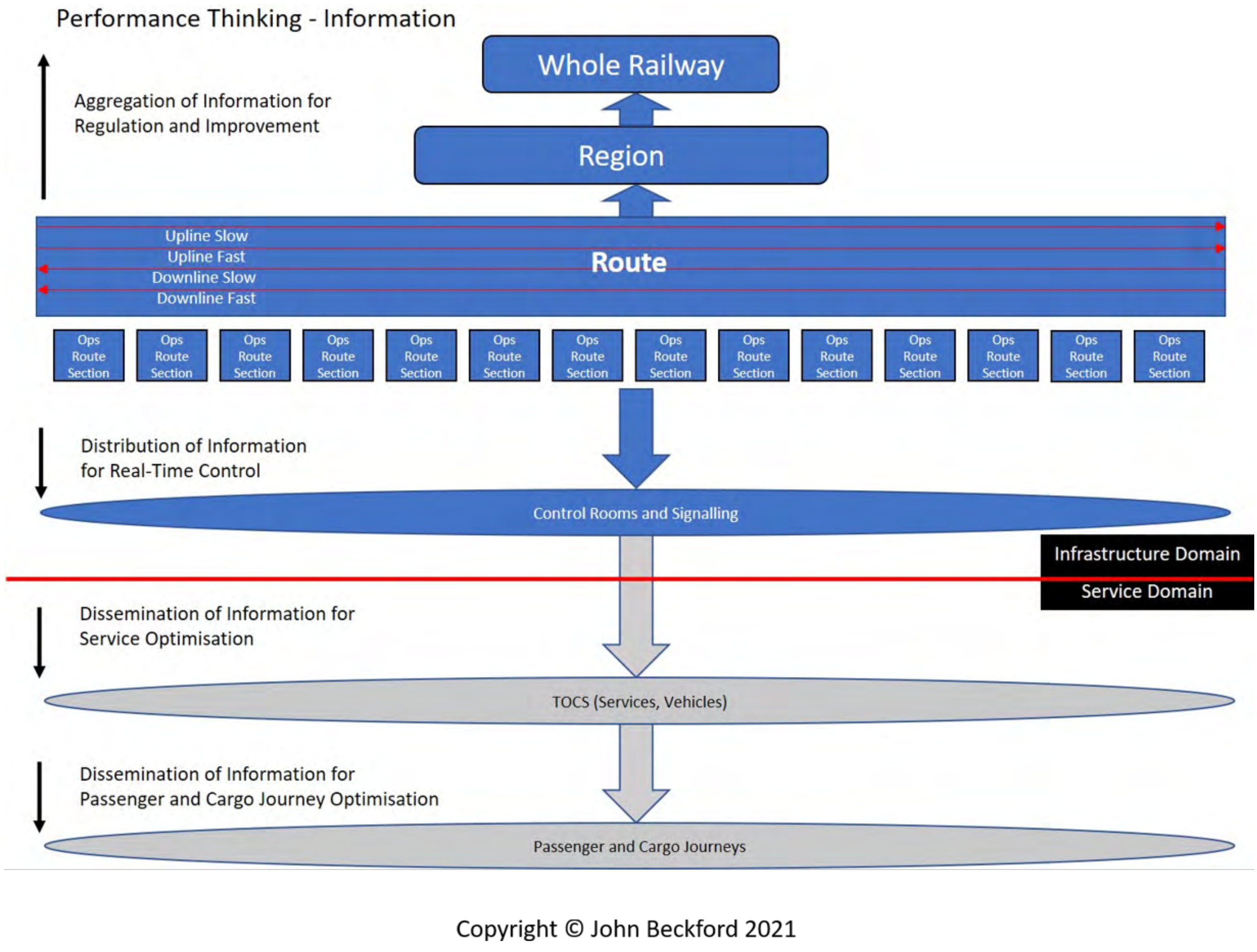

Figure 4: Conceptual Model 2

it is dependent and which are dependent upon it.

Progress on the Seasonally Agnostic Railway

Initial models were created that successfully demonstrated the logic of the model using synthesised data.

During November 2021 working prototypes of the SAR Model, using both real and synthesised data, have been demonstrated to both the Rail Industry 'Seasonal Challenge Steering Group' (which includes representatives from all major parts of the industry) and the Central Engineering Leadership Team from Network Rail. The model received enthusiastic endorsement from both groups and the demonstrations have secured their support in closing data gaps and enabling access to key supporting resources.

Key findings from SAR development

The SAR model is a substantial work in progress that is expected to be in development for two or more years beyond the date of writing. It is a substantial contributor to the 10 Year Weather Resilience Strategy of the UK Rail Industry and is both challenging and informing the short- and long-term actions and activities.

There are for now a number of key findings from the work in relation to asset data:

- It is held in different systems for different purposes, there is no single source of 'truth';
- Data management, capture, curation and use all appear weak;
- Much is held in unstructured or unsearchable form (for example, in a standards document) where it cannot easily be retrieved or applied;
- We have not yet been able to identify specifications or standards for some assets;
- The process of data retrieval is currently very labour intensive;
- Much decision making about managing incidents and risks relies on the personal knowledge and expertise of individual asset managers, more than on systematic application of data. Consideration of this expertise is to be addressed in the subsequent phases of the work.

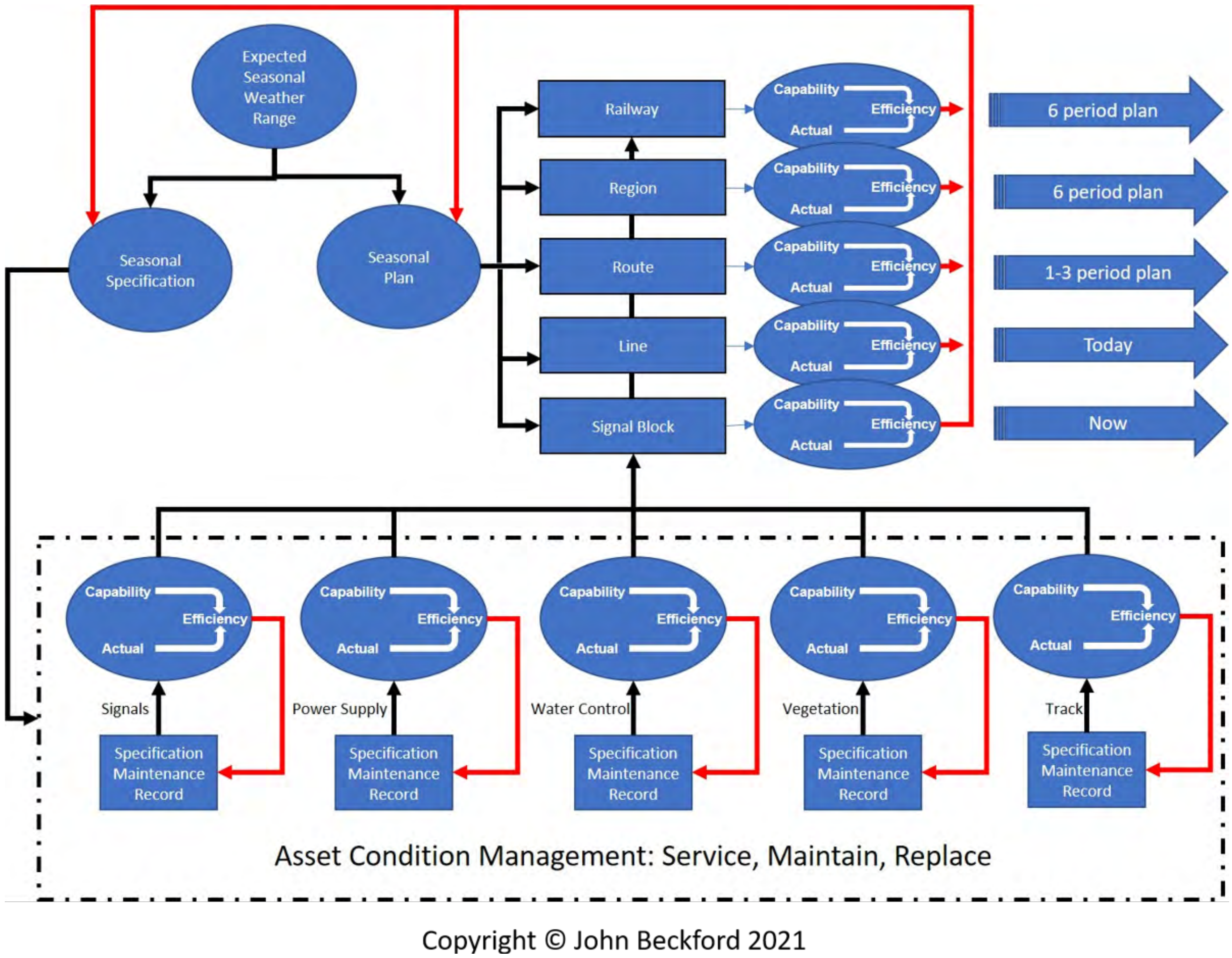

Figure 5: Conceptual Model 3

The emerging model is being designed to deal with the challenges of dirty or absent data, though this will clearly have an impact on forecasting accuracy.

Section 3: Discussion and transferable learnings

Our preliminary conclusions in relation to the project under consideration and the specific ambition to develop safer complex systems are that there are systemic issues with railway data that have implications for operational safety and performance. The SAR is intended to help overcome these. The challenges are:

- Inadequacy of change management processes;
- Failure to integrate new tools with old;
- Culture, behaviours;
- Approach to management is fragmented, siloed, unsystemic;
- Lack of meaningful information;
- Scale and rate of change are substantial matters.

It would be reasonable to expect that many of the issues identified with Network Rail would be replicated in any other large scale, mature infrastructure system and that similar challenges would apply.

It would be equally reasonable to assert that a systemic approach to modelling the organisation in the manner outlined here and informed by a similar understanding would enable identification of ways in which risk could be reduced and performance enhanced for any other similar? organisation.

The utility of the systemic approach rooted in cybernetics is becoming apparent and the ability to embrace the entire 'hard' aspects of the system are proving invaluable as is the idea of structural recursion in which an invariant data structure (in effect a fractal) applied to each ORS enables rapid scaling and application of the approach to multiple locations simultaneously without the need for large scale interventions.

There are transferable lessons to be developed about the:

- Design and implementation of new systems;
- User awareness and education;
- Identification structuring and organisation of data;

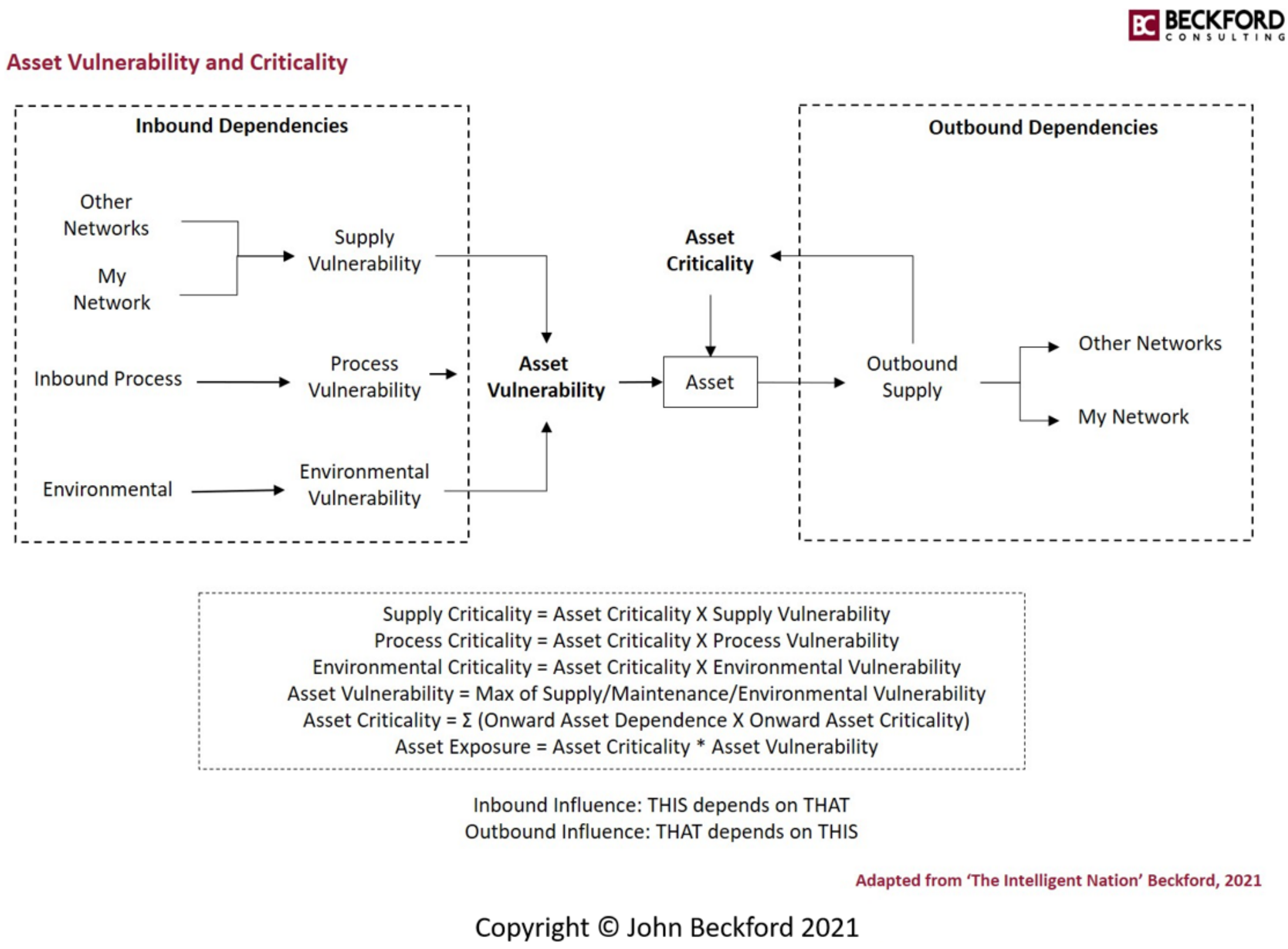

Figure 6: Conceptual Model 4

- Multi-partner working in complex systems diagnosis and therapy;
- The risks arising from siloed thinking and imparted to complex systems;
- The use of positional power and influence to demand solutions that are 'right now' rather than 'right';
- The challenges facing any mature infrastructure organisation in addressing complex, data-based challenges from within the traditional expertise and knowledge base of the particular sector.

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Ro Ro passenger ferry safety: The capsizing of the Herald of Free Enterprise

By Prof Chengi Kuo, Prof Dracos Vassalos

Executive summary: The unlearned safety lessons from the capsize of the Ro Ro passenger ferry the Herald of Free Enterprise at Zeebrugge in 1987 are explored. The key finding: safety is a "non-absolute entity" and closely integrated with impact assessment and a revolving management system. The generic design of safety management methodology is applicable universally.

Tags: transport, maritime, design for safety, safety management methodology, safety culture, corporate manslaughter law, complexity, system interfaces, damage stability, Belgium

Section 1: Background and introduction

The case study addresses the capsizing of the passenger Ro-Ro (Roll-on/Roll-off) ferry the Herald of Free Enterprise. In spite of a public inquiry and other studies carried out following this accident, there are still unlearned lessons, as is normal with accidents involving complex systems if examined under a different lens. There are many examples supporting this. For example, the Titanic accident was finally explained through a forensic study undertaken on the 100th anniversary of the disaster; the Estonia accident was explained by a Swedish Government-funded research project 10 years after the accident and following several investigations, reports and conspiracy theories; and the Derbyshire accident was eventually resolved 10 years later following a series of UK Government-funded research projects. The lens considered in this study relates to the nature of safety and its measurement. In particular, the lack of safety systems, which addresses quantitatively what we call 'safety level' by assigning risk credit to all contributions to safety and then informing decision makers of which actions to take cost-effectively in a consistent and rational manner. This applies to the safety of all complex systems. In this respect, safety is addressed though design (built-in safety) and operation (management of residual risk), targeting the requisite resilience to ensure a fail-safe system. A combination of these two approaches leads to what could generically be called, Design for Safety Management, so that life-cycle issues could be accounted for in a structured approach.

As such, fundamental features relevant to safety management involve the nature of safety, assessment of significant innovative concepts and the critical role of management per se. These topics are important because all related industries must meet challenging targets pertaining not only to safety of life onboard, but also encompassing environmental and financial hazards. As such, the experience from shipping can be shared widely. For example, the shipping industry is actively considering the use of Green House Gas (GHG)-less fuels, such as hydrogen and ammonia, as alternative marine fuels despite there being very little operational safety experience.

This case study highlights the complex nature of passenger ferry operations and examines the fundamental safety features. These were shared and discussed with colleagues in the profession via an internet questionnaire, leading to the conclusion that a Design for Safety Management methodology could assist in enhancing the safety of Ro-Ro ferry operations.

Ro-Ro passenger ferry operation as a complex system

The ferry operations have several key stakeholders, the principal ones being the passengers, the owner, the ship itself, port operators, regulatory bodies, suppliers and the wider public. The activities are dominated by human performance to meet a number of demanding and conflicting requirements, such as 52-7-24 operations under intense commercial pressure and international competition, bounded by national and international rules and regulations and served by multi-national and multi-cultural crews. At the same time, there is a need for good management, a positive attitude and behaviour, including effective communication, to ensure the ship operation is profitable venue.

The multifaceted interactions between the various activities are extremely complex and some are non-absolute entities where there is no unique right/correct or wrong/incorrect solution. This is not helped by the fact that safety itself is a non-absolute entity, thus introducing additional challenges.

About the accident

The vessel was operated by Townsend Car Ferries Limited (a subsidiary of P & O), and its normal routes were Dover-Calais and Dover-Zeebrugge. At 18:05 hours on 6 March 1987 she left the inner harbour at Zeebrugge, bound for Dover, with a crew of 80 on board plus 81 cars, 47 freight vehicles and approximate 460 passengers. There was a light easterly breeze, and the sea was calm. Four minutes after leaving the harbour, she capsized with complete sinking prevented by the fact that she was still in shallow seas. Water rapidly filled the vessel below the surface level, ending up with at least 150 passengers and 38 crew members losing their lives.

The capsizing was caused by several adverse factors acting together, the key ones being:

- Open bow door: The bow door must be closed when the ship is in motion, but there is a tendency to leave it open at the start of a journey to clear the fumes from the loaded vehicles. In this case, the bow door was left open as the person assigned this duty was asleep due to over work.
- Ship trim forward: This means that the vessel happened to have its bow immersed beyond level keel. This factor combined with the bow door being open meant that sea water rapidly entered the car deck. This triggered a reduction in the stability of the vessel, leading it to capsize.
- Ship was turning at high speed: The vessel quickly reached 14 knots and turned to port, thus introducing an additional heeling moment. The angle of lurch very quickly reached 30o and gradually increased to 90o until she was lying on her side.

Section 2: Analysis and insights

Analysis

The case study analyses the capsizing of the Ro- Ro passenger ferry Herald of Free Enterprise in 1987. It is not unreasonable to ask the following question:

> *The accident happened more than 34 years ago and, after a public inquiry and many studies, are there any lessons still to be learned?*

The argument presented in the introduction, namely that in the absence of a structured approach to addressing safety where all key contributing factors could be consistently measured and accounted for, leads to the following key observations:

1. Implication of safety as a non-absolute entity;
2. The use and limitations of a prescriptive regulatory approach to addressing safety;
3. Impact of significant innovations and the need to be assessed critically from a total system context;
4. The safety of complex systems is strongly affected by interfaces as they can disrupt continuity;
5. The role of management is critical to determining the quality of safety.

Implication of safety as a non-absolute entity

Safety is a word everyone knows, but how it is understood by various parties can differ. Safety is associated with meeting a goal, and this is best illustrated by an everyday example relating to crossing a busy road without being injured by the traffic. How this task is performed is dependent on personal perception of what is safe and not safe. Pedestrian A may stand at a traffic junction and wait for the green light before crossing and this can take a few minutes. Pedestrian B may decide to cross the same road at any point when he or she thinks traffic is clear. In fact, there is no correct or incorrect way of crossing a road. In other words, safety is NOT an absolute entity. When safety is addressed, by an individual, an organisation, a nation or an international body, for any situation it assumes that safety is a specific absolute entity, and the effectiveness would vary depending on its closeness to reality. To overcome this feature, it is essential for decision makers to continually re-assess the process via an iterative safety management system circuit while applying a combination of understanding, reviewing of available data, analytical assessment and practical insights.

In general, an organisation, such as a shipping company, would select a safety standard (or risk level) and train its staff to implement it in practice. The term 'risk' is used, unfortunately, by many people to mean both 'hazard' and 'risk' in an inter-changeable way. A hazard can be regarded as an obstacle that prevents the objective being met. Risk is a two-parameter term represented as the product of likelihood of a hazard becoming a reality and the level of its consequences. People working in the operation may not understand the theoretical background to deriving the magnitude of risk of a specific hazard, but instead make their risk judgement based on the guidelines given, personal experience and probability of occurrence because consequence is usually regarded as intolerable or undesirable. Sometimes individuals can misjudge the risk and that may lead to human errors.

The use and limitations of a prescriptive regulatory approach

In most situations, safety is assessed based on prescriptive regulations devised and implemented by a regulatory body. The prescriptive principle is illustrated by an everyday example involving buying a cheesecake from Marks & Spencer, see **Figure 1**.

As can be seen, both the requirement and the method of solution are prescribed. This is a familiar concept to everyone: in childhood, it is the parents at home, at school it is the teacher, etc. In life, there seems to always be someone who is prescribing what one has to do. This, in turn, has led to the belief that this is the way that everything, including safety, should be treated.

However, it has to be recognised that the regulatory approach assumes safety is an absolute entity for two main reasons:

- Firstly, the regulatory body needs a reference standard for users in practical applications. For example, it would be unsafe and unworkable in the present day to let car drivers decide what speed they should drive on public roads.
- Secondly, once the reference is established it will allow the regulatory body to enforce the regulations and also to achieve consistency.

This approach is workable under most circumstances if hazards are known, and their risk levels are fairly constant and readily predictable.

Unfortunately, there are situations where these conditions are not available. For example, hazards changing and their risk level being unpredictable, such as the Covid-19 variants known as Alpha and Delta that appeared in the UK and worldwide in 2020-21 and are now being actively monitored and examined.

Significant innovations need to be critically assessed in a 'total systems' context

In the 1960s the desire to take one's own car to the European continent across the English Channel required a very good reason and patience as the car was treated as cargo. On arriving at the quay side, the driver and other passengers went on board while the car was loaded. At the end of the crossing, they had to wait while the car was unloaded. Overall, the journey across the channel could take as long as half a day.

It was a significant innovation when the open deck concept was developed, and one or more decks became open spaces where cars and lorries could drive on and off with minimum delay. The process of driving onto the ferry (Rolling on) and driving from the ferry (Rolling off), was given the name Ro-Ro. The introduction of this concept of crossing the channel was most attractive, particularly so with the freight operators. For example, fresh fruits and vegetables could be loaded onto a lorry in the south of Spain and be available in the North of Scotland within 48 hours without any adjustment to the loads.

However, like many situations in practice, there is a technical 'Achilles' heel' to the concept. If water found its way to the open deck, even a small quantity, the induced heeling moment could overcome the designed ship restoring capacity, normally determined by the ship weight (displacement) and the magnitude of the restoring lever, which is called GZ. **Figure 2** shows a vessel in various rolled positions (angles) against the values of GZ (intact ship). Regulations at the time did not account for the impact of water on deck These were enforced after the Estonia accident, in 1987, through what is known as the Stockholm Agreement, based on physical model experiments.

This means that the safety of a significant innovation must be assessed by a different method to that used traditionally via prescriptive regulations. In principle, a 'safety case' approach should be used to assess the safety implications of each innovation so that hazards with intolerable risk levels can be identified to ensure ferry operators give special attention to reduce the risk of any new feature. From a management point of view, there is also a need to understand any deficiencies and put appropriate measures in place to ensure that the residual risk from this 'Achilles' heel' is properly managed at all times.

Influences of safety interfaces on a complex system

It should be recognised that ferry operation is complex because

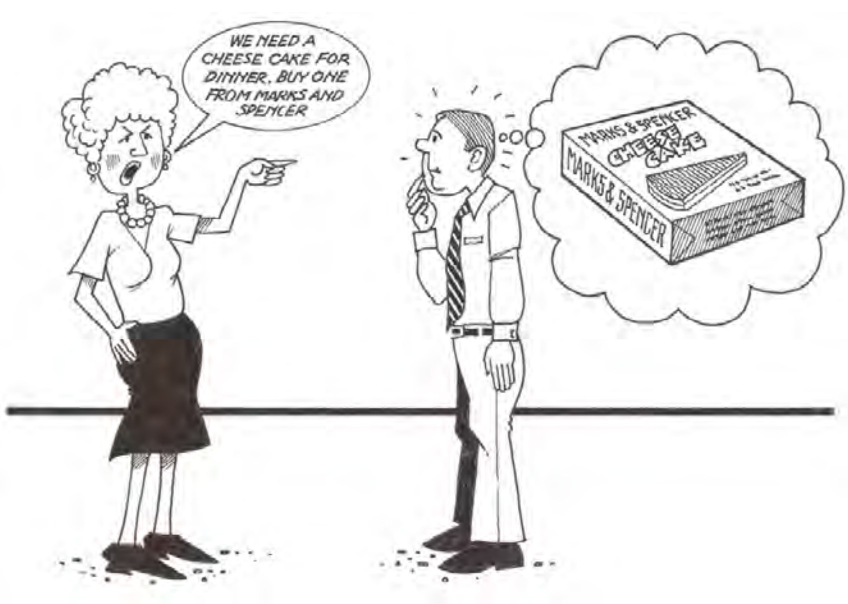

Figure 1: Buying a cheesecake for dinner.

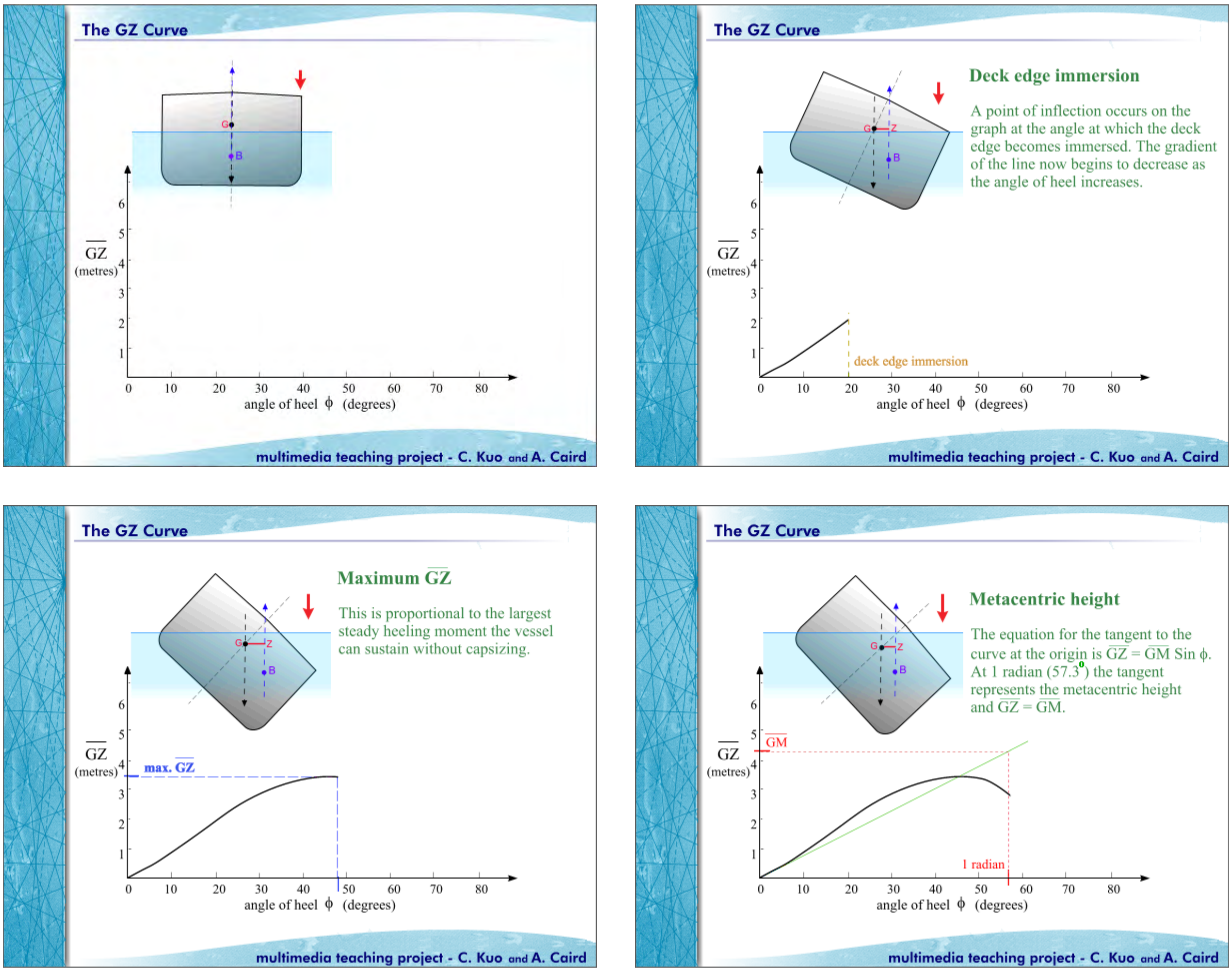

Figure 2: Animation to illustrate ship stability.

there are many system interfaces. This term is used here to mean interaction between different systems, including humans, while performing a task. The following are the main interfaces:

- Software-hardware: such as a prescribed process to be followed by equipment in performing operations;
- Software to software: the linking of two or more computer programs together into a larger software application;
- Hardware-hardware: combining the use of two supplied components in the design of equipment;
- Human-hardware: for example, the wearing of personal protection equipment when performing a hazardous activity;
- Human-software: when a human user implements a specific procedure in practice;
- Human-human: how a group of people work together or how two or more groups work together.

From experience, safety failures can usually be traced from these interfaces.

Interfaces in the following Ro-Ro ferry operations are relevant:

- Operating a novel design: It is assessed using the traditional marine safety regulatory approach, which does not take into account that new operations introduce new hazards with different risk levels.
- Commercial pressure: Ferry operations are very competitive because shipping is an international business. The demand for crossing the English Channel is very high, especially during the summer school holiday period.
- Operational procedure: For the reasons given in (b) above, the operational times are tight with rapid turnaround at ports. The short crossing route serves a large number of vehicles. In winter months, the schedules are affected by adverse weather conditions.
- Workload: The workload is high for the crew as the operation runs on a 52-7-24 schedule and key members are often heavily committed, leading to fatigue and, in turn, human errors.

- Crew communication: Ships are usually operated by crew from various countries with different cultural backgrounds and varying levels of language skills. This requires good communication between crew, especially during the busy periods.
- Politics: In any situation there can be problems with human-to-human interface and the term 'politics' is often used to describe the conflict of interest. These incidents can be unintentional as well as intentional. As an example, those operating onshore may not understand fully the working conditions of those working on board, leading to less co-ordinated operations.

The role of management in the quality of safety

As in any organisation, management plays a key role in all activities and, in particular, safety. It is the management team that decides on policies, development of organisational culture and makes decisions on a range of issues that include investment and commitment of funds. Safety has not been given top priority for many reasons. Two key reasons being:

Firstly, the boards of companies tend to focus their attention on short term issues, such as profit levels and investments for good return. Safety is regarded as an 'add on' expense, which should be minimised.

Secondly, there is a lack of understanding of the importance of safety and the critical responsibilities for safety assurance. This was identified in the public inquiry conducted under Justice Sheen.

However, there was a special change to the law in the UK for addressing safety as a result of the Herald of Free Enterprise accident that is often not recognised generally. It is concerned with the introduction of corporate manslaughter into the legal framework relating to safety. The effort was promoted by the Disaster Action charity, which was formed after the Zeebrugge ferry accident. Yet, it took 20 years before this became law. In the simplest terms, this law stipulates that instead of putting blame only on the actual person(s) responsible for the root cause of the failure and fining the board, the fault should also be attributed to the Board of Directors and that those responsible for safety may be jailed in the case of a fatality. The passing of this law in 2007 ensured a concentration of minds on safety at board level.

Insights

Seeking the views of colleagues in the profession

Having identified unlearned safety lessons, it was decided to seek the views of colleagues in the maritime safety profession by designing a special questionnaire and circulated it to those with responsibility for safety, or those involved in related safety projects. An example of the latter includes those who have been actively involved and participating in the STAB conferences, which are held every three years at different locations around the world.

The results of the questionnaire are given in the Appendix whilst key findings are highlighted in **Table 1**.

Main findings of the investigation

A summary of the main findings can be considered under the following headings:

- What went wrong? There are several aspects, and these include: The status of the bow door was not readily observable, and, in this case, it was left open due to human error when the ship departed from the port. Available draft gauges giving the loading conditions were not accurate enough. The location of the ship's centre of gravity was uncertain – it is a key stability parameter and was obtained by experiment when the ship was built, but over the years modifications were made and extra facilities added that changed the location. The company's management team was described as 'rotten to the core' in the public inquiry and it was unclear who was

Item	Issue considered	Agreement level
1	Safety is a non-absolute entity	70%
2	Management features involved in marine accidents	93%
3	Better understanding: safety factors	73%
4	Greater awareness of the management role	74%
5	Insufficient attention given to near misses	76%
6	Lessons: Higher safety for new GHG-less fuels	75%
7	Better awareness of management and management systems	78%

Table 1: Summary of key findings from the questionnaire responses of maritime safety professionals

responsible for the safety of the vessel.

- What aspects would improve safety? Firstly, a recognition by more people that safety is not only a technological matter but must consider other features such as human factors relating to attitude, behaviour, performance etc. and hence the complex nature of the system. Secondly, a "good level" of safety can only achieved when it is properly managed or, in other words, the need for good management at all levels.
- What potentially worse outcomes were avoided? These include the following: firstly, the ship capsized close to shore and in shallow waters, making emergency rescue operations more readily available and effective. The ship was busy, but not at its peak or running during the busiest operating times where there could have been more fatalities.

A design for safety management methodology

In the offshore oil and gas industry the treatment of safety was changed from using a prescriptive regulatory approach to a goal-based approach, namely the safety case approach, after the explosion of the Piper Alpha installation on 8 July 1988. The report from the public inquiry, popularly known as the Cullen report, made 108 recommendations and these included the use of a safety case approach. The methodology is based on system engineering when the safety of a system is examined by asking the following set of questions: What aspect can go wrong (or hazard identification); how likely that would be (probability of occurrence); and how serious are the likely outcomes (consequences), with the product of the latter two giving a risk estimation. In addition, it includes what to do when 'things' go wrong (emergency preparedness and response). These tasks are then managed by a linear safety management system. There is no doubt that this is an enhancement. Since safety involves both technical and management aspects, research has led to design for safety management that can integrate technical and management features. This thinking and method could be used widely, for example to examine the safety of ships using GHG-less fuels, such as hydrogen and ammonia.

Section 3: Discussion and transferable learnings

Overall lessons learned

The lessons for general safety derived from this case study can be summarised as follows:

- The safety of significant innovative ideas and solutions should be assessed in the total system context and by a systems engineering approach so that hazards with intolerable risk are identified and appropriate mitigation steps taken.
- The accident could have been prevented if management had given safety higher priority, thus ensuring there was a positive safety culture within the whole organisation, including attention to safety procedures such as closing the bow door before the ship sets sail.
- In the light of this accident and many investigations and research studies, there are now fresh guidelines and regulations on passenger Ro-Ro ferry operations plus greater safety awareness that would reduce the probability of similar accidents occurring, including enhanced resilience leading to a 'fail safe' system.

The target audience for this case study

There are many target audiences for the outcome of this case study:

- The prime target audience is the maritime and offshore industries. In the former, the focus is on maritime transport, which is responsible for 90% of bulk goods, and great effort is being devoted to the use of GHG-less fuel such as hydrogen and ammonia. Presently there is little operational safety experience. It is also relevant for those involved in generating offshore renewable marine energy where efforts are focused on floating systems where safety must meet both maritime and offshore regulatory requirements.
- Another target audience is land-based industries where safety is critical, such as the nuclear industry and the car industry developing autonomous vehicles. The lessons from this case study are fundamental and could be applied to addressing similar problems faced by these industries.
- Generally speaking, where safety of a complex system is concerned, the arguments presented, and the lessons learned are directly relevant and readily transferable.

Looking to the future

To achieve safer operations in a complex system, a number of suggestions are outlined here.

Firstly, it must be recognised that safety must be managed to achieve a desirable standard and this needs to be done at all levels. Top management has many responsibilities and a crucial one is the development of a positive safety culture within the organisation.

Secondly, there is a need for greater safety awareness by all stakeholders. One method of achieving this goal is conducting a number of focused active interactive workshops for the wider spectrum of stakeholders in order to improve communication and understanding. These should include addressing fundamental safety issues and its management as well as providing experience via simplified group exercises.

Design for safety management as a transferable methodology

This case study has shown the roles of technology and management and their interdependence. There is, therefore, a need to integrate these factors. An effective method would be to adopt the concept of design for safety management that can combine the advances made in design for safety with the application of management techniques to provide an effective and transferable methodology.

Appendix – results from the questionnaire

a) About the responders: There is a wide range of organisations with ship operations (28%) and consultancy (18%) being the largest groups (**Figure 3**).

b) Over 83% of the responders have either good or very good knowledge on safety

c) There is a general agreement (around 70%) relating to the impact on the non-absolute nature of safety; the regulatory approach assumes safety is absolute as a reference standard and enforcement, while the prescriptive regulatory approach would be unsuitable for complex safety systems (**Figure 4**).

d) The attitude of people is regarded (by 27%) as contributing most significantly to marine accidents and this is followed by the wrong procedure, lack of information and communication breakdown, with poor management

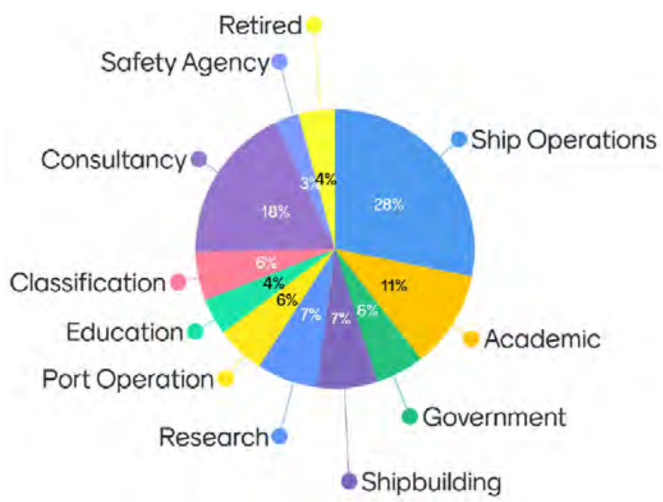

Figure 3: Background of the responders to the questionnaire.

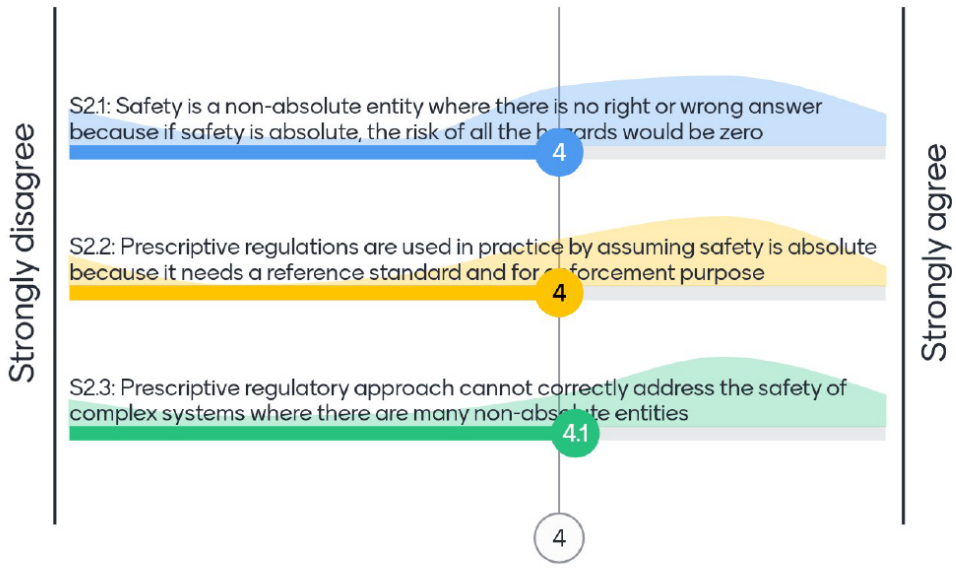

Figure 4: Findings of views on the non-absolute nature of safety.

receiving 17%. Yet, all the previous four factors are dependent on management. The total represents 93% (**Figure 5**).

e) General agreement on the lessons learnt from the Ro-Ro ferry accident, with more attention given to near misses (77%), better understanding of the role of management, better understanding of factors influencing safety and reduction in potential future accidents sharing equal scores (**Figure 6**).

f) The most significant benefits from the investigation were considered to be improved safety understanding and greater safety awareness in the industry (52%) (**Figure 7**).

g) Safety lessons for general application led to high agreement on the need for GHG-less fuels aiming to achieve a safety standard as high as reasonably practicable (78%) and technical people could benefit from some understanding of management and management system (78%) (**Figure 8**).

All industries could learn from maritime accidents for the following key reasons: understanding human factors, grasp of the non-absolute nature of safety and the important role of management.

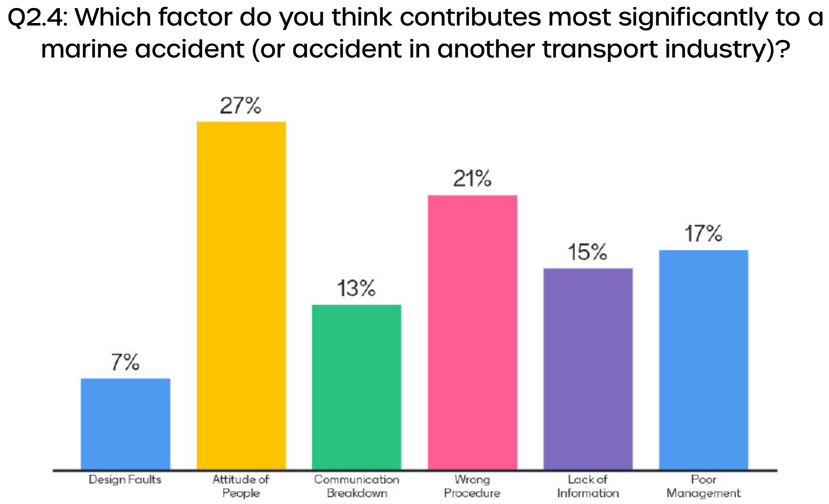

Figure 5: The factors that contribute to marine accidents

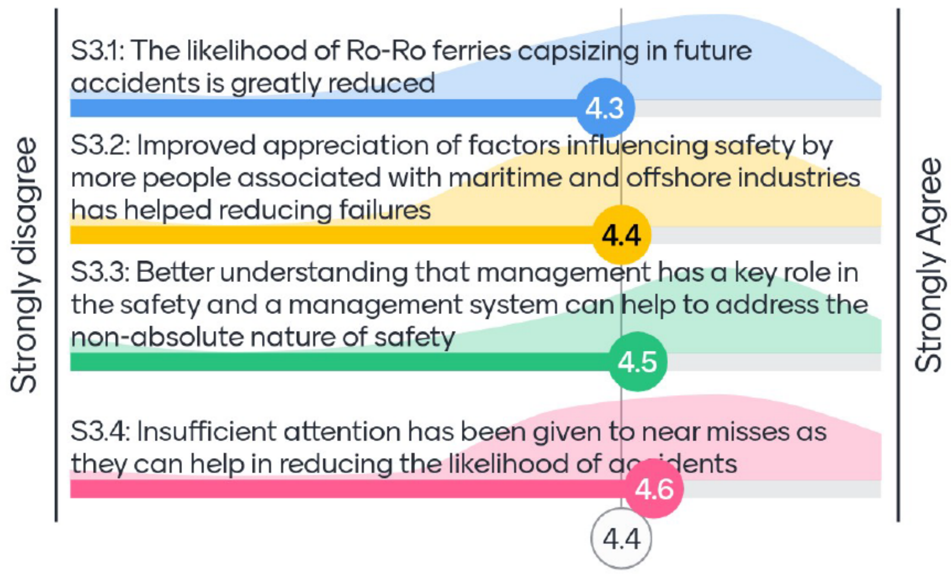

Figure 6: Lessons learned from Ro-Ro ferry accidents

Q3.6: What do you think is the most significant improvement to Ro-Ro ferry safety deriving from the investigations?

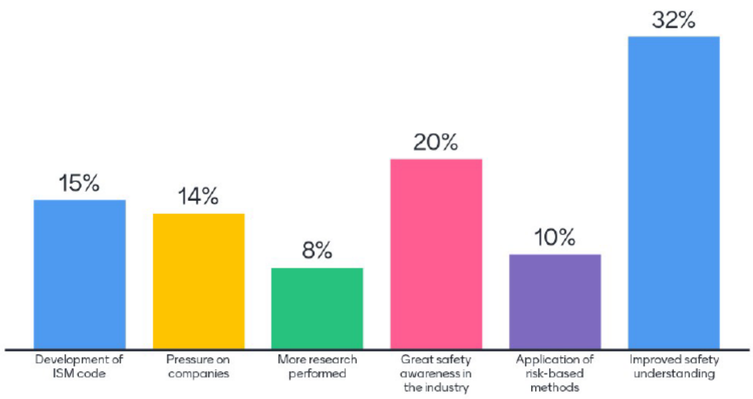

Figure 7: Factors contributing to improvements in Ro-Ro ferry safety

Q4: Safety lessons for general application

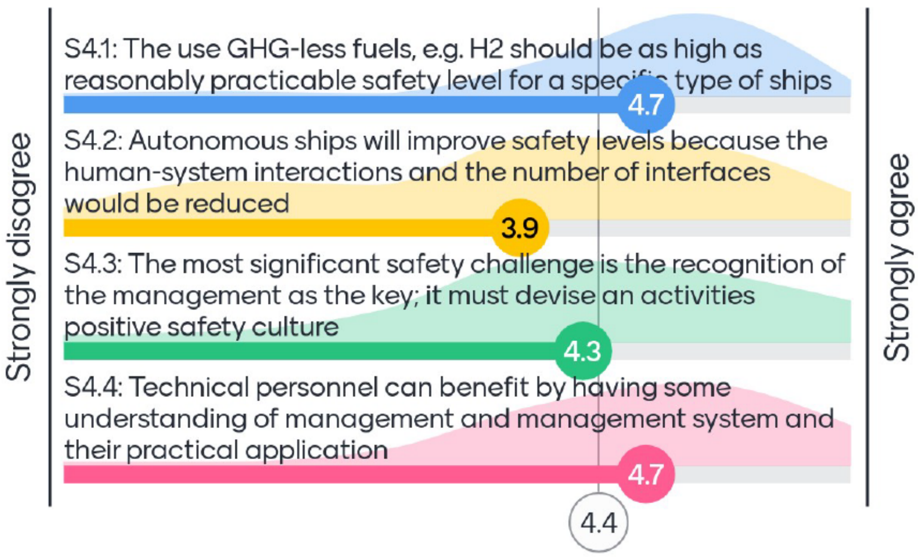

Figure 8: Findings of safety lessons for general application

In summary, the findings of the questionnaire have provided good guidance on how safety management can be adopted in practice and how safety lessons learned from Ro-Ro passenger ferry accidents can assist in enhancing the safety of complex systems.

Acknowledgements

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Towards intelligent dynamics of an active transport system for biking

By Prof Andrés Medaglia, Maria Wilches-Mogollon, Prof Olga Sarmiento, Dr Felipe Montes, Dr Luis Guzman, Prof Mauricio Sanchez-Silva, Prof Ronaldo Menezes, Dr Darío Hidalgo, Karla Parra, Andrés Useche, Dr Hansel Ochoa-Montero, Natalia Rodríguez, Lorena Salamanca

Executive summary: Due to the COVID-19 pandemic, Bogotá (Colombia) created 84 km of temporary bike paths to reduce SARS-COV-2 transmission in the public transport system. We developed a methodology that integrates complex systems modelling with data analytics to understand the impact of the temporary bike paths on the system's dynamics, complexity, mobility, health, and safety. The methodology and results could serve other cities that are implementing temporary bike paths and transforming their transport systems.

Tags: temporary bike paths, COVID-19 pandemic, sustainable transportation, urban, Colombia, South America, Global South, group model building, causal loop diagram, agent-based modelling

Section 1: Background and introduction

On 11 March 2020, the World Health Organization publicly declared COVID-19 as a pandemic. At the same time, the Colombian Government declared the country to be in a state of health and sanitary emergency due to the COVID-19 pandemic. This declaration mobilised multiple government sectors to devise strategies to cope with this new global public health scenario.

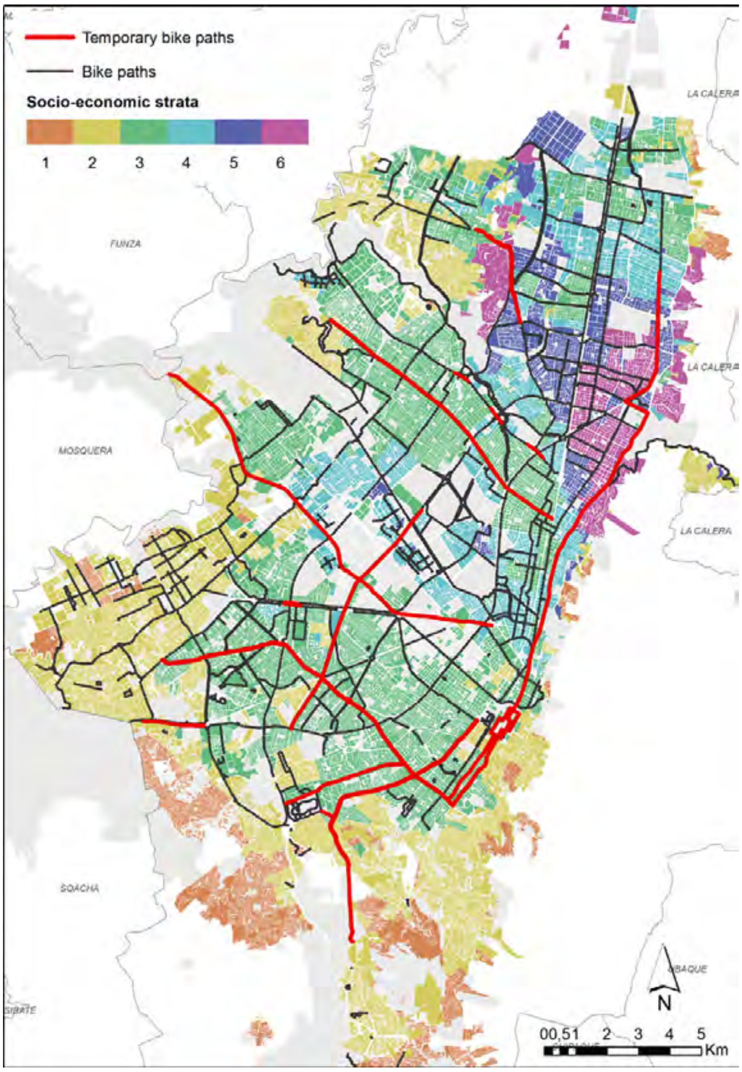
On 20 March 2020, the city of Bogotá (Colombia) entered a strict lockdown. The Mobility Secretariat, the public agency in charge of urban transport, looked for innovative ways to guarantee mobility throughout the city, while reducing the agglomeration of the public transport system, to meet the physical distancing measures recommended to decrease SARS-CoV-2 transmission [1]. Just before the pandemic, 34% of the daily trips generated in Bogotá were made using public transport, the most used mode of transport in the city [2]. The public transport system was considered a public service with a high risk of transmission. Based on the established bike culture in the city, the bicycle was targeted as the primary solution.

As a solution, temporary bike paths were created covering 84 km of the city road network [3]. The initiative was a coordinated action between the Mobility Secretariat, the Recreation and Sports Institute of Bogotá (acronym in Spanish is IDRD), TransMilenio (Bogotá's Bus Rapid Transit system agency) and the National Police. The idea of the temporary bike paths was to connect the existing infrastructure, to mirror main transport corridors and to provide access to peripheral neighbourhoods and surrounding municipalities (**Figure 1**). This policy made Bogotá one of the first cities in the world to conceive the bicycle as an inclusive transport solution during the COVID-19 pandemic. By June 2021, 21km of the temporary bike paths were transformed into permanent bike paths and 28km of temporary bike paths are still in place.

The case of Bogotá has also served as an example for implementing bike paths in other cities around the world during the COVID-19 pandemic. Globally, governments have incentivised cycling as a low-cost, healthy, sustainable, equitable and space-saving mode of transport that reduces the risk of COVID-19 transmission [4]. By July 2020, at least 94 cities in 20 countries from the Americas, Europe, Asia and Oceania had implemented or expanded bike paths to support social distancing and traffic safety [5]. Thus, the fast provision of new bike infrastructure during the COVID-19 pandemic in a city like Bogotá, from a middle-income country, is a suitable policy to assess its safety and health potential impacts.

In this context, the aims of the case study are to:

- Describe the performance of Bogotá's bicycle transport system and the measures taken to manage the COVID-19 pandemic, integrating complex-systems modelling and data



a) Map of Bogotá in 2020 with permanent and temporary bike paths

b) Temporary bike path

c) Temporary bike path that became permanent

Figure 1. (a) Map of Bogotá in 2020 with the geographic distribution of permanent (black lines) and temporary bike paths (red lines). The coloured areas are block units and their colour denotes the socio-economic strata (1 being the lowest income; and 6 the highest income). Photographs of (b) a temporary bike path and (c) a temporary bike path that evolved into a permanent bike path.

analytics (henceforth referred as to systems analytics);

- Evaluate the potential impact of policy decisions on the bicycle system in terms of safety, health, efficiency and flexibility; and
- Provide evidence of the potential impact that an emerging transport system could have on preventing SARS-CoV-2 transmission.

Bogotá's bicycle transport system

In Bogotá's bicycle transport system bicycle users interact with other road agents, such as pedestrians, motorised vehicles and other active transport vehicles, on a mixed-use road network and the bicycle path network. The system performance is the result of the dynamic interaction of a physical infrastructure, a set of rules for using the infrastructure, and decisions made by regulators that enforce the correct use of the system and can modify the infrastructure and its rules. Through its use and regulation, different stakeholders seek to satisfy the needs of bicycle users and improve their conditions to generate more trips in this mode. Appendix A shows the description of the system´s missional activities through the TASCOI tool [6].

For this case study, we analyse the bicycle transport system of Bogotá in 2019 and 2020. We consider the year 2019 as the baseline period for the evaluation, as the system was operating without disruption. The year 2020 is the follow-up period, when the COVID-19 pandemic appeared as the major disruptor, challenging the system's performance (**Figure 1**).

Section 2: Analysis and insights

System analytics and methodology

We propose a systems analytics methodology to understand the impact of the temporary bike paths on the system's dynamics and complexity; and assess their impact on the system's performance. The methodology relies on integrating systems theory with data analytics. Systems theory allows us to describe the system's complexity and understand its dynamics. Data analysis allows us to compute the system's metrics (i.e., indicators) and predict changes in the system via statistical and machine learning models. Our methodology allows the stakeholders to measure the users' reaction to the system's transformations and design actions (or controls) to prevent possible systemic failures.

Figure 2 presents the proposed systems analytics methodology. From the left, using the Group Model Building (GMB) methodology, we define the complex system, its boundaries, its dynamic rules and the system's functionality metrics by deriving a causal loop diagram co-created with the stakeholders (boxes 1 and 2). Box 3 shows an Agent-Based Model (ABM) [7] that simulates different scenarios for the system and estimates its KPIs. Based on the systemic approach (output from boxes 1 and 2) and the assessment of the system's metrics estimated by the ABM (output from box 3), box 4 shows the step where stakeholders design and evaluate different scenarios regarding infrastructure changes. Then, in box 5, the decision maker selects those policy interventions that best meet the stakeholders' interests, in terms of safety and efficiency of the system, and use the results of the evaluation to support the decisions regarding the policy's implementation. As time passes by, the system adapts, and the system's actors react to those interventions. New data is generated based on the interaction with the intervened system. Box 6 shows the step where new data is collected to re-estimate the KPIs through the recalibration of the statistical and machine learning models following an observation period. Boxes 7 through 10 show the data analysis components of our methodology, with their key inputs and outputs labelled in their incoming and outgoing arcs, respectively. Boxes 7 and 8 show the steps where we calculate the collision rates and the Level of Traffic Stress (LTS) classification at a granular scale (e.g., street level). These two KPIs proved significant when modelling the cyclists' behaviours and are proxies of the safety of our system. Box 9 shows the step in the methodology where the mobility patterns are inferred from the Origin-Destination (OD) matrix. Box 10 shows the third KPI of the system, namely, the physical activity assessment as a primary benefit from using the bicycle. This KPI is assessed through the estimation of the metabolic equivalents (METs) generated while using the bicycle and through the Health Economic Assessment Tool (HEAT) [8] which estimates the impact of the physical activity on prevented mortality through an economic value assessment. Finally, the collision rates, the LTS, and the mobility patterns (outputs from boxes 7, 8, 9) feed the ABM (inputs to box 3). Appendix B describes the methodology for each box.

Application of the systems analytics methodology to Bogotá's bicycle transport system

We applied the systems analytics methodology to Bogotá's bicycle transport system. Through a Group Model Building (GMB) with stakeholders we created a Causal Loop Diagram (CLD) with the main variables that describe the systems behaviour. These variables can be grouped into six domains:

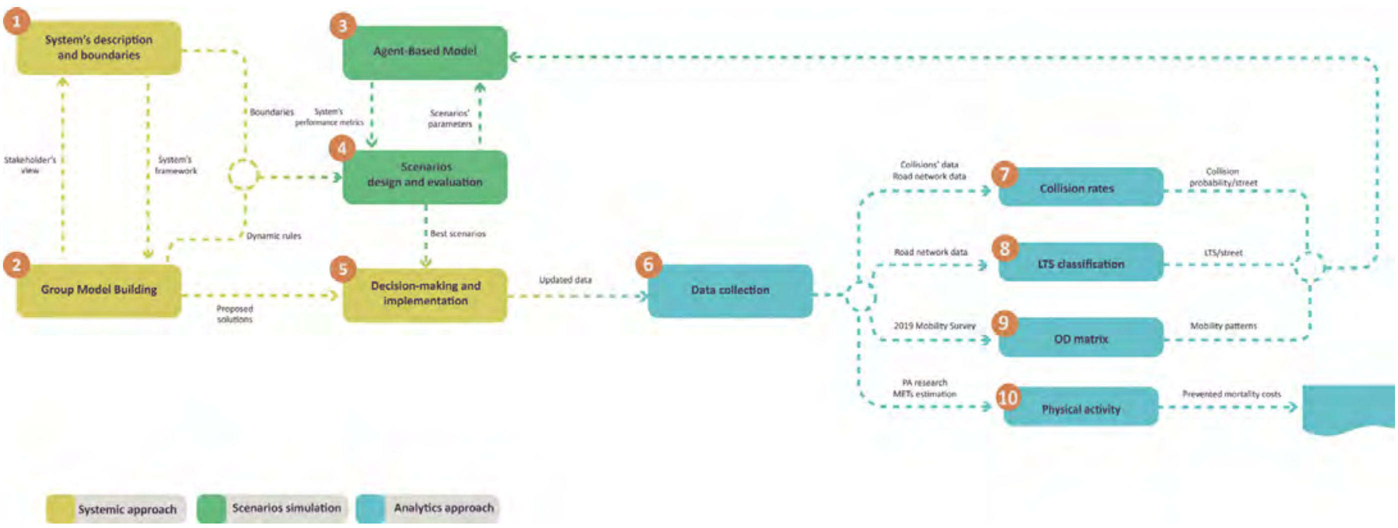


Figure 2. Systems analytics methodology (PA: physical activity; LTS: level of traffic stress; OD: Origin-Destination matrix).

civic culture, cycling motivation, substitute transport modes, quality of life, infrastructure for bicycle use and citizen participation (**Figure 3** and Appendix C). After understanding the different perspectives of the stakeholders, we described the system's complexity, following the University of York's framework [9].

Figure 4 describes the bicycle transport system in Bogotá as a complex system, following the University of York's framework [9]. Our system description is based on the system identity and dynamics described by the TASCOI tool and the CLD built by the stakeholders. The transport system described in **Figure 4** unfolds the complexity in six major elements: causes of complexity; consequences of complexity; exacerbating factors; design-time controls; operation-time controls; and possible systemic failures.

The leading causes of complexity are the heterogeneity in the rules and the system's evolution

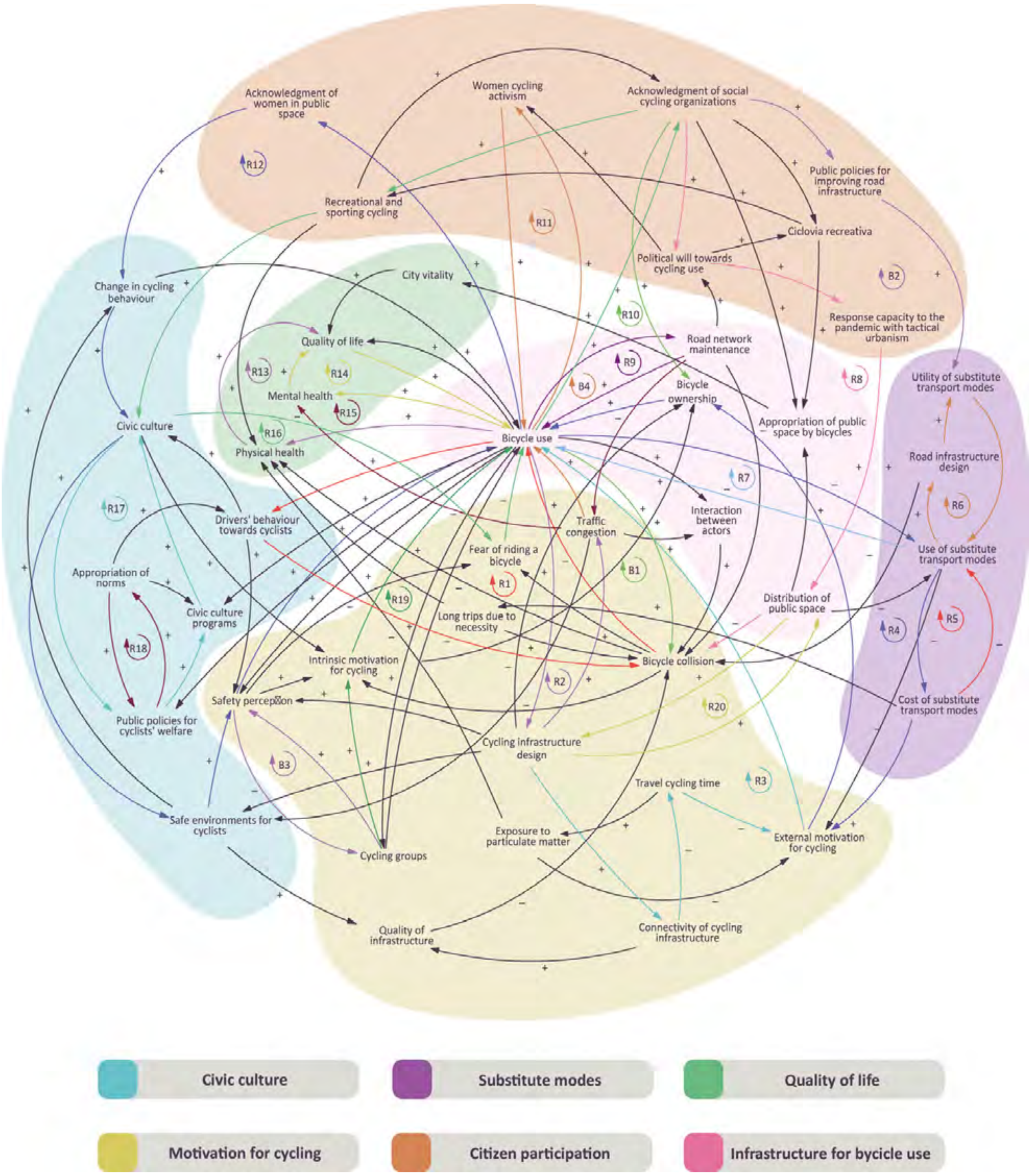


Figure 3. Causal loop diagram of Bogotá's bicycle transport system

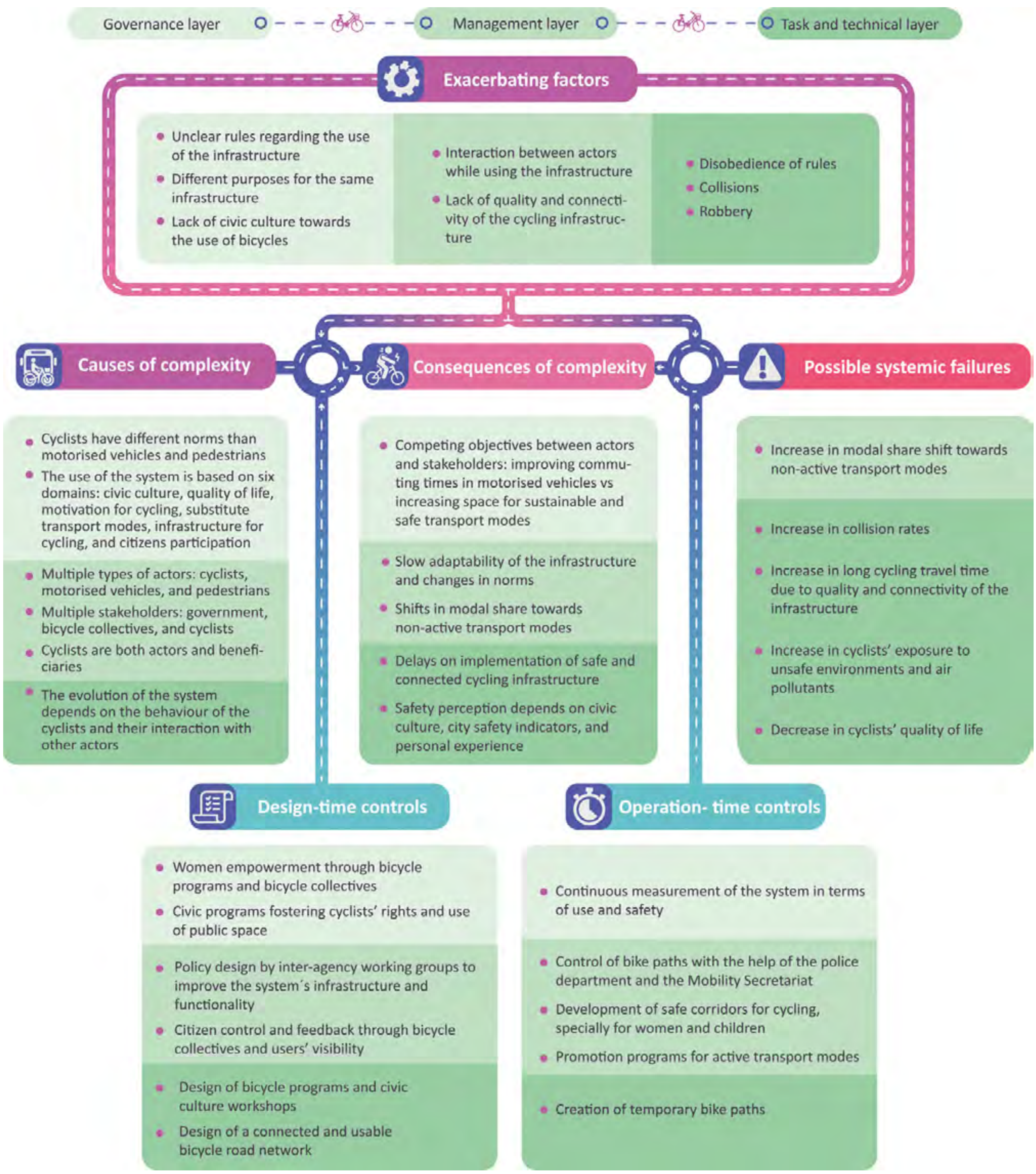


Figure 4. Complex system description via the Complex Systems Framework by the University of York

that relies on the same actors, specifically on the interaction among bicycle users with the infrastructure and other road agents. These causes of complexity, exacerbated by some factors and alleviated by design-time controls, have consequences. The system adapts slowly and competing objectives create an ever-increasing tension between motorised and alternative transport mode actors.

As shown on the CLD, six variable domains affect the system's behaviour. Identifying these domains was vital for describing the exacerbating factors, where civic culture and motivation for cycling appear consistently in each layer. In addition, women empowerment and programmes to promote bicycle use are critical design-time controls that affect the system's behaviour.

With the help of the stakeholders, we identified five possible systemic failures that impact the safety of bicycle users. The failures vary from a shift toward non-active transport modes to bicycle users' safety. Two of the most critical possible systemic failures are an increase in collision rates among bicycle users and a decrease in quality of life due to high levels of traffic stress, pollutants, and unsafe environments.

To reduce the likelihood of a systemic failure, we identified at least one operation-time control at every system's layer. These controls continuously improve the system's operation in terms of use, safety and security; and explicitly involve new underrepresented groups, such as women and children. In particular, the creation of temporary bike paths is one of those controls designed and implemented during the COVID-19 pandemic. In this case study, particularly in the simulation model, we evaluate the impact of the temporary bike paths, as operation-time controls, on the possible systemic failures related to a rise in collision rates and stress levels.

Analysis of the impact of the temporary bike paths on the performance of the system

Scenarios

After describing the complexity of Bogotá's bicycle transport system, we assessed the KPIs for 2019 and 2020 and implemented the ABM to analyse the impact of the bike paths on the system's performance. Our analysis considered three scenarios: 1) baseline scenario in 2019 (henceforth called scenario 1); 2) follow-up scenario in 2020 with temporary bike paths (henceforth called scenario 2); and 3) hypothetical scenario in 2020 without temporary bike paths (henceforth called scenario 3).

Level of traffic stress

As for the LTS, our first KPI of the system, **Figure 5**, shows the classified segments for a) 2019 and b) 2020. More notably, for 2020, 73% of the road segments were classified as LTS low, increasing by 4% compared to the baseline of 2019. In addition, the reduction of more stressful road segments, classified as LTS 2, 3 and 4, shows a significant reduction in the overall LTS of the city. We partially attribute these changes to the temporary bike paths, which took over a lane of the road for bicycles and changed these segments' speed, congestion, density and flow.

Collision analysis

As for our second KPI, the mean monthly collision rate for 2019 was 1.37 per 1,000 cyclists, while the mean collision rate for 2020 was 0.97. These rates show a significant reduction of 29.73% between 2019 and 2020.

In the same way, the median collision rate per ZAT (acronym in Spanish for Transport Analysis Zone) for 2019 was 23.62 collisions per 100 million VKmT, while the median collision rate for 2020 was 13.46 collisions per 100 million VKmT. These rates show a significant reduction of 43% between 2019 and 2020. **Figure 6** shows the monthly collision rate per 100 million VKmT for each ZAT in a) 2019 and b) 2020.

We further investigated the change in monthly collision rates of the ZATs where the temporary bike paths were implemented. For these ZATs, the mean monthly collision rate reduces from 64.69 to 38.94, which shows that there was a significant reduction of 45% in the collision rate per ZAT.

Agent-based model (ABM)

The ABM combines the two previously described KPIs to estimate the bicycle transport system's performance. When analysing the number of collisions, scenario 3 (hypothetical, without temporary bike paths) estimates 56% more collisions than scenario 2 (follow-up, with temporary bike paths). This result shows that the operation-time control of implementing the temporary bike paths in the city made this complex system safer compared to the hypothetical scenario without temporary bike paths. Regarding LTS distribution per travelled meter, scenario 2 LTS Low increased by 6.22%, while the other LTS were reduced by 2% on average, compared to scenarios 1 and 3.

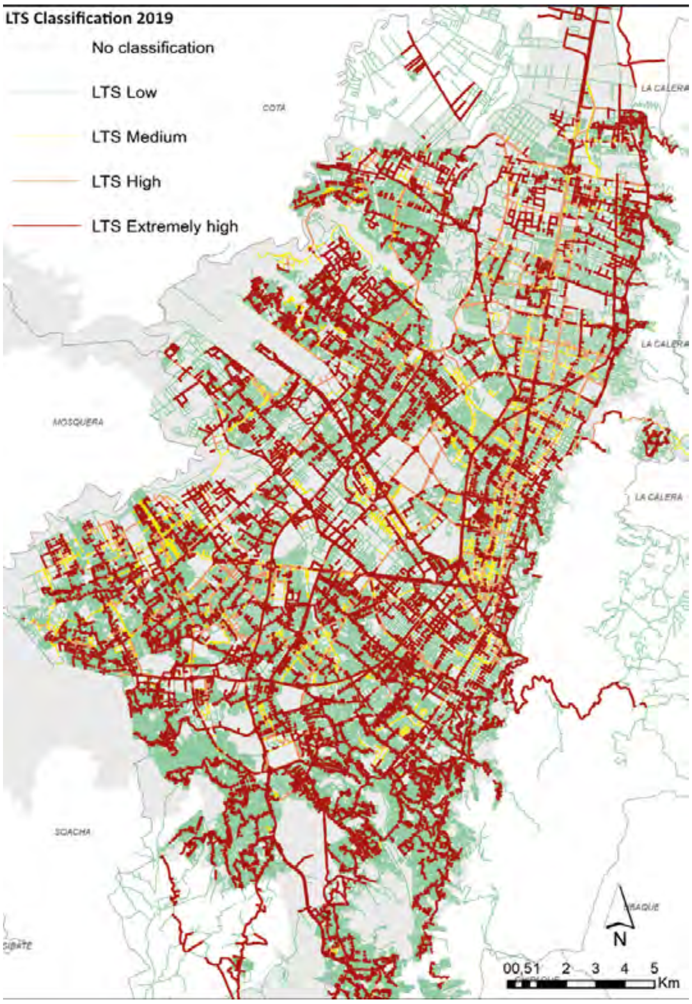
Physical activity

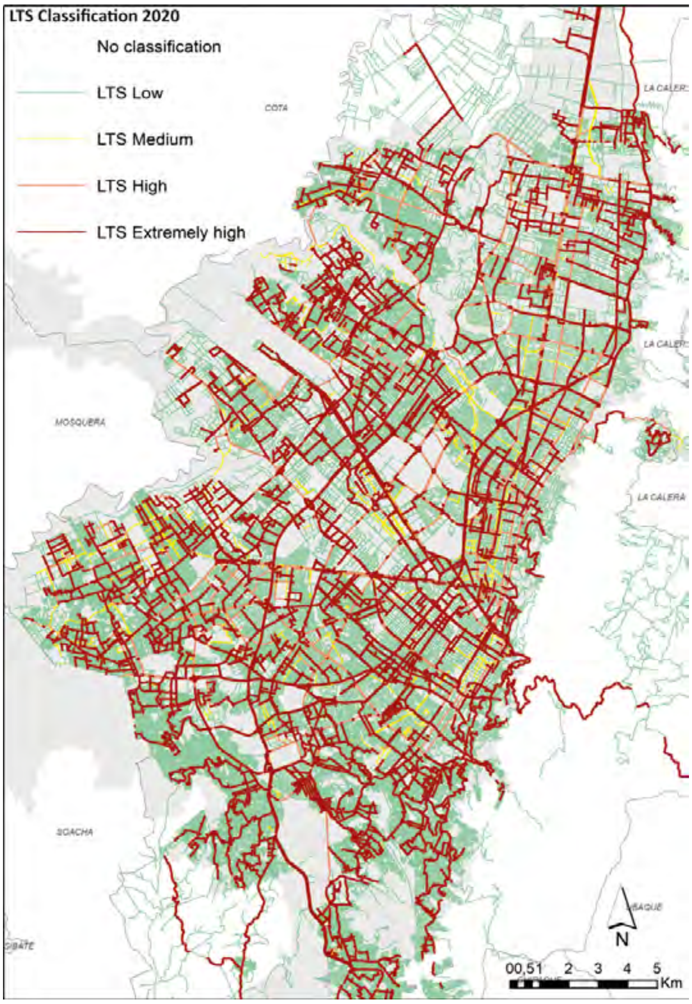
The third KPI measured for the system was physical activity. The average METs per trip for 2019 and 2020 are 236.27. The average METs for bicycle users per person per day are 506.54. As we assume that the only change from 2019 to 2020 is the total number of daily trips in Bogotá, the average METs generated per day in Bogotá for using a bicycle as a transport mode in 2019 are 126.46 million, while in 2020 they are 93.58 million. Therefore, the reduction in METs for 2020 depends only on the reduction of daily trips by bicycle. This reduction could have been up to 60% if the number of trips per day had remained constant [10], and 34% if the bicycle transport system had followed the same level of activity as the city [11].

Furthermore, we estimated the health and economic value of the bicycle transport system of Bogotá. The analysis using the HEAT tool shows that in 2019 the prevented premature deaths were 199 with an economic value of 224 million euros. In 2020, the prevented premature deaths were 145 with an economic value of 164 million euros. The number of prevented deaths and the economic impact attributed to the amount of physical activity generated by cycling in 2020 is not negligible.

Stakeholder's perspective

We held a meeting with the system's primary stakeholders to gather their feedback on our results. At the meeting, staff from the Mobility Secretariat discussed the study results and possible





2019 (scenarios 1 and 3)

2020 (scenario 2)

Figure 5. Maps with road segments classified by LTS levels for (a) 2019 (scenarios 1 and 3) and (b) 2020 (scenario 2)

ways the study could support decision making.

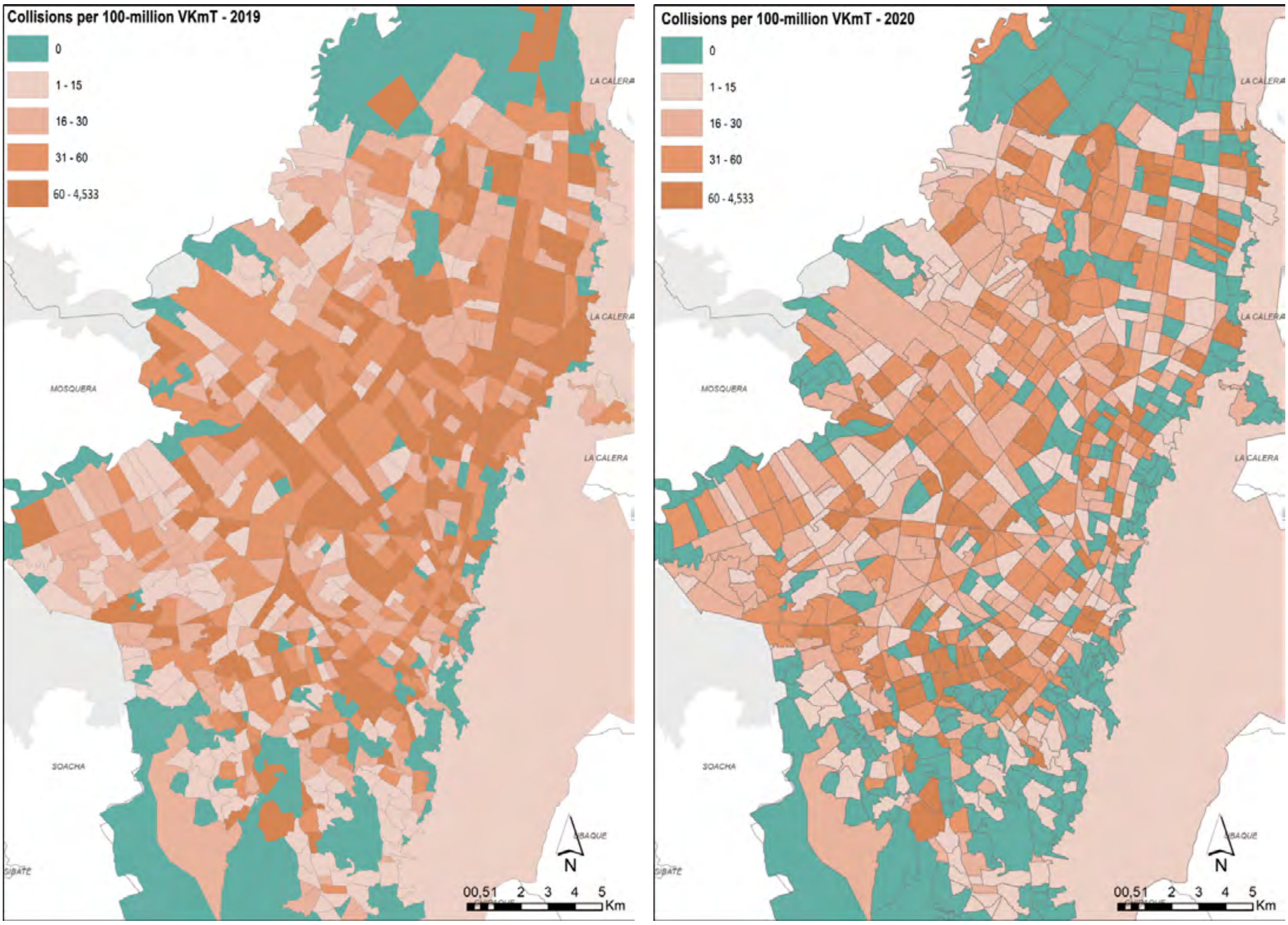
Stakeholders reported that the case study results could be used to diagnose the system and the impact of the intervention. In addition, the study is essential for the city's Mobility Master Plan and Land Use Master Plan, where more bike paths will be supported. Finally, the Bicycle Manager for Bogotá stated: "We consider it fundamental to show this study to the local bicycle councils to bring academy closer to policy decisions and to improve Bogotá's bicycle transport system."

The stakeholders also reported that the findings of the CLD reinforce the idea of developing social infrastructure in the city. Along this line, the Mobility Secretariat is currently working with the community to create safer infrastructure supported by the improved bike culture. Also, an ongoing project of the Mobility Secretariat related to the case study is the creation of the Mobility Observatory, from which they plan to share data dynamically and understandably with citizens. Our project could certainly support this initiative.

Finally, in terms of follow-up studies for the city, next steps could consider emissions of air pollutants; how bicycles impact these emissions; and estimate the risk for cyclists in terms of inhaled dose and respiratory diseases. Likewise, other studies could focus on expanding the methodology to prescribe actions related to the network's connectivity and flow segment analysis.

Section 3: Discussion and transferable learnings

This case study describes and assesses the city's response towards the COVID-19 pandemic and its evidence of the importance of creating exclusive bike paths for cyclists in Bogotá. Temporary bike paths are part of a complex and multidimensional system. This system was associated with mitigation of the risk of a systemic failure as it could reduce collision rates, increase the meters of segments with low levels of traffic stress and continue promoting physical activity, which



2019 (scenarios 1 and 3) 2020 (scenario 2)

Figure 6. Maps of mean monthly collision rates per 100 million VKmT per ZAT for (a) 2019 (scenarios 1 and 3) and (b) 2020 (scenario 2)

in turn is associated with yearly prevented premature deaths. Local stakeholders recognised the importance of this study in supporting the Mobility Master Plan, the Land Use Master Plan and the Mobility Observatory. The evaluation of this system has required local and international support and a multidisciplinary group with partnerships among researchers, stakeholders and the community. Further research is needed to investigate whether this change is persistent and whether similar results can be achieved in situations outside the context of the COVID-19 pandemic.

During the COVID-19 pandemic, governments worldwide have incentivised cycling by provisionally redistributing road space. By July 2020, at least 94 cities in 20 countries created or expanded bike paths. In many of these cities, the implementation of temporary bikeways has involved legal disputes [12] and ongoing discussions about the right to use the space [12,13]. In North America, much of the controversy has focused on how to access opportunities for safe active mobility. Furthermore, it is important to underscore that although collision rates have decreased in the United States, United Kingdom, Germany, Spain and Canada, motor vehicle fatality rates, injury accidents and speeding violations have increased and remained elevated when traffic levels began returning to pre-pandemic conditions [14] [15]. Specifically, in Colombia, the total death rate for cyclists also increased from 0.84 to 0.87 per 100,000 inhabitants in 2020 [15]. Our study shows that bicycle collisions decreased during the COVID-19 pandemic and collisions could have been higher without the implementation of the cycling system infrastructure.

In this context, cities that implemented temporary bike paths and are willing to increase the number of kilometres of permanent bike paths could be the basis of a similar study to compare their results with ours as the proposed methodology is based on a local perspective. In conjunction with political and community support, these results could serve to advocate for the implementation of a safe biking infrastructure for promoting cycling, which is a healthy, sustainable, equitable and space-saving mode of transport that reduces the risk of COVID-19 transmission.

Several components of our methodology and results could serve as an example to other cities in the world. First, the GMB workshop and the CLD showed the different dimensions of the system's dynamics, where infrastructure, civic culture, motivation for cycling, citizens' participation, substitute modes and quality of life affect the system's performance. This transdisciplinary and broad perspective helped us describe the system's complexity broadly, considering the performance indicators and the stakeholders' perspectives.

The response of the city towards the imminent threat of a pandemic served as an excellent operation-time control. In addition to reducing collision rates and the LTS, the temporary bike paths presented the bicycle users with a transitional, yet flexible, intervention of the city. However, for future interventions, such as transforming the temporary bike paths into permanent ones, other road network users, such as buses, cars and motorcycles, should be involved in a more comprehensive cost-benefit analysis as their systems may be affected.

The findings of this case study are directed to local and global policymakers, regulators, NGOs and bicycle collectives related to transport systems in a broad sense. Local and global policymakers could find this case study helpful in understanding the system's complexity, including multiple factors that affect safety when transforming the infrastructure. This study could be used as a first step analysis for estimating the possible impacts that future interventions may cause in the collision rates and LTS of the system. On the other hand, the system's regulators can use the description of the system's complexity and the CLD to reinforce their vigilance over the system and select key variables to monitor and address with local governments.

The case study successfully shows how flexible the bicycle systems are and how temporary interventions can be helpful for global policymakers. Furthermore, this case study could help cities where the funding for active transport is low. Finally, it shows that regardless of the type of bicycle infrastructure, the delimitation of paths for the exclusive use of bicycles improves safety for users.

The case study shows the importance of approaching systems with a systems analytics perspective. This perspective integrates qualitative and quantitative analysis of the system and an agent-based model where data and the individual behaviour of the agents empower and complement the predictive power of the models.

To improve safety, the system should be constantly monitored and measured in terms of collision rates, number of users and users' purposes, segment flows, collision hotspots, robbery and safety perception. The monitoring could be performed by creating intersectoral alliances for developing passive data collection instruments and robust surveys. Furthermore, the system's interventions should be based on the experience of the bicycle users, the behaviour of those users and the interactions with other motorised and non-motorised vehicles.

The system's success can be measured in terms of number of users, number of women and children riding bicycles, collision rates, quality of life, physical activity promotion and prevention of premature deaths. In this sense, success would be an improvement in multimodal transport in the city and an improvement in the quality and connectivity of the bicycle infrastructure that responds to the users' needs.

Appendix A. TASCOI tool

Figure 7 shows the system's four missional activities (transformations). The first activity, commuting, is carried out by cyclists whose purpose is to mobilise throughout the city. In this activity, the system's performance depends directly on the decisions cyclists make while they use the infrastructure and their interaction with other actors. These decisions can be affected by the level of stress of each segment, the security and connectivity of the route and the perception of risk of collision of each segment. Government agencies collaborate with cyclists to facilitate commuting, creating regulations guiding the correct use of the infrastructure and developing safer and more connected infrastructure. The second activity, infrastructure maintenance and development, is conducted by government agencies and by bicycle collectives, which work together, but from different angles, to design and create better infrastructure. They both transform the existing cycling infrastructure for the benefit of cyclists. The third activity, public policy development and enforcement, is performed by several government agencies in coordination, which adjust and implement new policies based on the system's performance measurements with the aim of improving the actors' wellbeing. Specific policies could negatively affect motorised vehicle users, as some of these policies may encourage the use of sustainable modes of transport over the others. The fourth activity, system monitoring, is performed by government agencies in charge of collecting data, analysing and providing evidence of the system behaviour. These agencies regularly

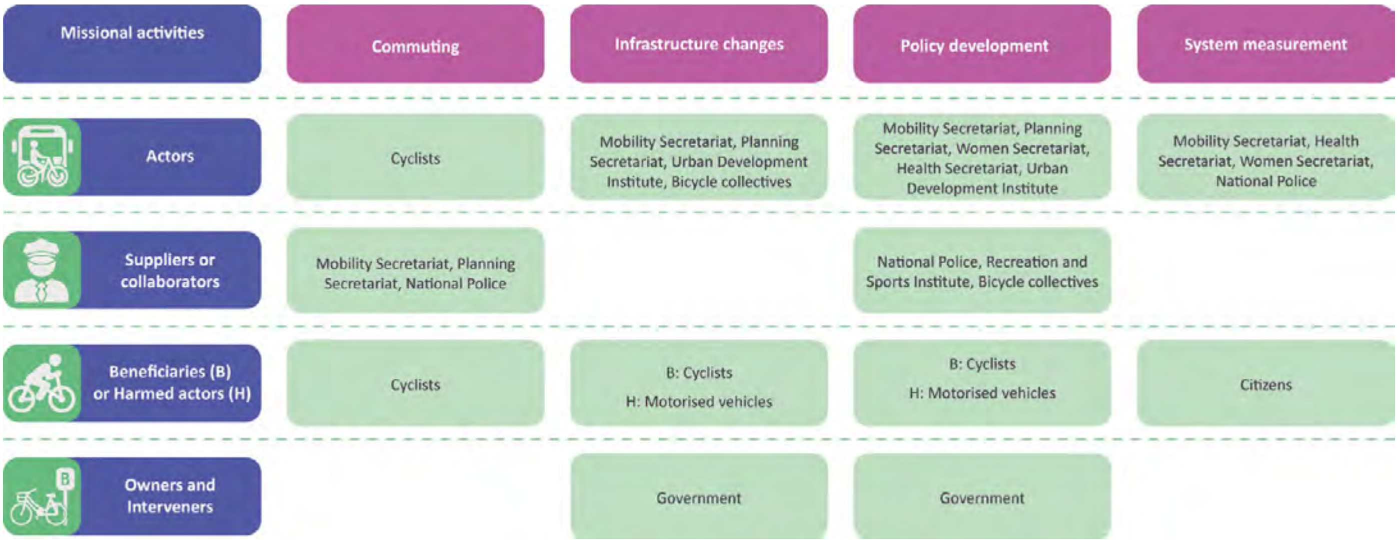


Figure 7. Stakeholders and main missional activities of Bogotá's bicycle transport system

collect and report statistics that assess collision rates, the volume of cyclists and perception of safety, among other outcomes.

Appendix B. Description of the main components of the system's analytics methodology

1. Group Model Building

Group Model Building (GMB) is a methodology for developing community-based system dynamics (CBSD) workshops to identify the system variables and individual worldviews of the actors involved [2,3]. The primary outcome of the GMB is a Causal Loop Diagram (CLD) that reflects the dynamics of the main variables of Bogotá's bicycle transport system. The GMB was developed through a workshop that included stakeholders of the system. The first part of the workshop comprised of an introductory session with a general presentation of the system and an overview of the complex systems approach. The workshop continued with a series of activities in working groups that generated a shared mental model of the system, modelled by a single shared CLD built by the working groups and further validated with semi-structured interviews with experts. Participants of the workshop and validators were selected according to their area of expertise to enrich the CLD with different perspectives.

For the case study, we conducted a half-day session via Zoom with Mural as the virtual blackboard, where participants developed the group activities. The whole session was recorded to facilitate the compilation and validation of the CLD. The workshop involved 17 participants representing the Health Secretariat, Planning Secretariat, Mobility Secretariat, Women Secretariat, bicycle activists and researchers. After the workshop, we conducted five interviews with bicycle users, motorised vehicles users, researchers and bicycle activists to validate the CLD. The CLD is a critical input to describe the system's complexity and to define the ABM's boundaries.

2. Agent-Based Model

The Agent-Based Model (ABM) recreates the use of the road network and the collision dynamics of Bogotá's bicycle users. The model simulates the commute of bicycle users (agents) to estimate the collision rate per year, flow density per segment and distribution of LTS per travelled meter. The model evaluates the impact of changes in the infrastructure on collision rates, road flow per year and LTS at the population level.

The environment where the agents move is the city's road network for 2020, with and without the temporary bike paths, divided into road segments. Each road segment has three initial attributes: LTS classification per segment, segment length and initial collision probability per segment. The methodology to determine the LTS level and initial collision probability per segment is described in Sections 2.4 and 2.5, respectively. The road segment length is estimated directly from the road network.

The agents of the model represent the bicycle users. Each agent has the following attributes: origin ZAT (acronym in Spanish for Transport Analysis Zone) and geographic location within the ZAT; destination ZAT and geographic location within the ZAT; and risk profile. The origin and destination zones are based on the OD matrix. The agents are classified into one of three risk profiles: risk-averse, risk-neutral and risk-prone. The risk profile is assigned randomly, following the distribution of risk profiles assessed in Bogotá [17] and Portland (Oregon, USA) [18], where cyclists are classified by the potential risk that they are willing to take regarding road segments' safety, depending on sociodemographic characteristics and travel distances.

In the ABM, each agent performs a round trip per day. The agent chooses between following the shortest path or a path that balances distance and risk. For the latter, each road segment has an aggregated weight that combines distance and risk. The selection of the route depends on the risk profile of each agent. For each trip, the model generates random probabilities that follow the collision probability for each segment to simulate a collision. If an agent suffers a collision, the agent becomes more prone to choosing the path that gives higher weight to the (low) risk over distance. After each trip, the risk profile of the agent and the safety index of each segment, which reflects the updated collision probability, are updated depending on the collisions that occurred in the trip. The model assumes that all agents have complete information about the safety index of the road network. **Figure 8** shows the logic of the ABM in a flow diagram. At the end of each trip, the model records the number of collisions, LTS distribution per travelled meter and the traversed segments. The results are summarised yearly.

We calibrated and validated the model based on annual collision records. After validating the model, we were able to estimate performance metrics for several scenarios. The ABM input parameters are travel rates,

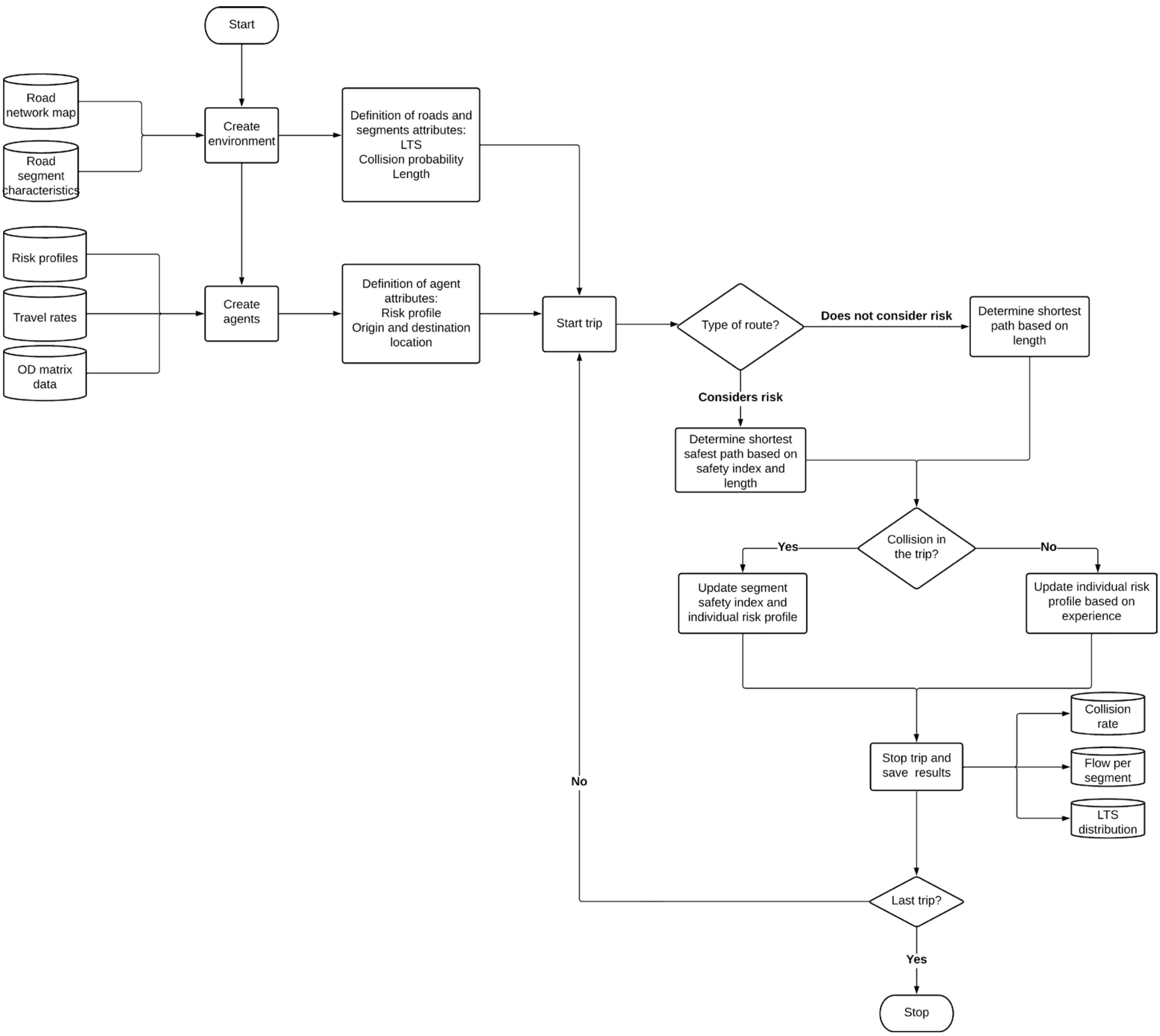


Figure 8. Flow diagram of the ABM

collision probability and the LTS per road segment. For this case study, we modelled three scenarios: 1) baseline scenario in 2019; 2) follow-up scenario in 2020 with temporary bike paths; and 3) follow-up scenario in 2020 without temporary bike paths.

We coded the ABM in JavaScript using the GAMMA 1.8 platform [19].

3. OD-matrix and cycling paths

Origin-Destination (OD) matrices describe the spatial distribution of daily trips. Although these matrices are usually generated for motorised vehicles, an OD matrix for bicycles is essential for decision makers to allocate resources effectively [20]. The OD estimation describes the zonal distribution of bicycle trips and the road network use at different (zone) levels. For our case study, the OD matrix is the source for estimating the most likely routes followed by cyclists and these routes, in turn, are vital for estimating the mean LTS per trip and the trip flows for each segment.

Higuera et al. [21] estimated an OD matrix for bicycles in Bogotá using the 2015 Mobility Survey. This OD matrix considered only mandatory trips during weekdays within Bogotá. The aggregation level of this OD matrix was the ZAT. The number of trips estimation for each OD pair used the sample design representative weights to recreate the city's dynamics. Following the same methodology, we estimated an OD matrix for the pre-pandemic baseline scenario (2019) using the 2019 Mobility Survey [2]. We considered only trips where the bicycle was the primary transport mode, with origin and destination within Bogotá's limits, and where the trip purpose is other than recreation and sport. The OD matrix (per day) expands to yearly trips, assuming the same daily travel pattern.

For the follow-up scenarios with (and without) temporary bike paths, we used the relative change in trips per day estimated by the Mobility Secretariat from 2019 to 2020 to expand the 2019 OD matrix. This estimation of the OD matrix assumes that neither the travel patterns of the cyclists nor the percentage of trips per OD pair changes.

4. Level of Traffic Stress

When commuting, bicycle users are exposed to different external stressors that can motivate or demotivate the use of the bicycle. One of the stressors is the road they use, which is related to being more likely to suffer a road accident [22–24]. The Level of Traffic Stress (LTS) is a proxy of the potential stress experienced by cyclists due to road network attributes [25,26]. This indicator estimates how much perceived stress a road segment imposes on a cyclist and can be used to plan infrastructure interventions that improve cycling as a mode of active transport.

Huertas et al. [27] developed a two-step machine learning methodology (unsupervised clustering and multinomial logistic regression) to classify the road network segments of Bogotá according to the LTS, using both physical and functional attributes. The methodology considers physical attributes of the road network, such as roadway width, number of lanes, presence of public transport lines and presence of cycling infrastructure, and functional attributes, such as congestion, traffic flow, traffic density, and vehicle speed.

Since 2018, several bike paths with different typologies have been implemented in Bogotá. Therefore, we extended the methodology to include the type of cycling infrastructure as a new input variable for this case study. According to the Colombian Transport Ministry [28], these types of cycling infrastructure are bike paths over the sidewalk with no segregation; bike paths over the sidewalk with physical segregation; bike paths over mixed-used roads with physical segregation; bus-bicycle paths; and unidirectional bike paths over the sidewalk.
We calibrated the model using new road network data for 2019 for the pre-COVID baseline and the new classification of cycling infrastructure. After calibration, we classified the 2019 and 2020 road segments. For the follow-up scenario (with temporary bike paths), the temporary bike paths were categorised as bike paths over mixed-used roads with physical segregation. For the vehicle speed in the road network, the speed of 2018 was used as a proxy for 2019, whereas the speed of 2021 was used as a proxy for 2020. This is due to data access limitations to the Google API engine, yet the traffic behaviour consistently captures the pre-and follow-up COVID scenarios.

5. Collision analysis

The collision rate is one of the main safety estimators for cyclists. This rate relates the number of bicycle users who ride in a zone of interest per day, month, or year to the number of collisions (fatal and non-fatal) registered in that zone. Thus, collision rates allow us to assess road safety and how it changes by year.

Carvajal et al. [29] developed a methodology to compare the collision rates in Bogotá per month. The methodology considers collision rates standardised by: (1) the total cyclists' population; and (2) the daily vehicle kilometres travelled (VKmT) per ZAT. The VKmT is estimated with the OD matrix.

We estimated the collision rates for cyclists in Bogotá per million cyclists and per ZAT per 100 million VKmT using the collision records for 2019 and 2020 and the 2019 Mobility Survey. We only considered collisions that involved a cyclist as an actor. The number of collisions per year was taken from the reported collisions in the SIMUR (acronym in Spanish for the Integrated Information System of

Urban and Regional Mobility), the official mobility database of the city fed with police records.

We used a Collision Predictive Model (CPM) based on a negative binomial regression model to estimate the probability of collision per segment for the ABM. This model reflects the relation between segment characteristics and collisions and predicts a collision rate per segment [30]. For the CPM, the independent variables are the number of road lanes, land use, type of bicycle infrastructure, vehicle congestion, vehicle speed, vehicle flow and segment width; and the dependent variable is the number of collisions per year for each segment. Then, we estimated the probability of collision per segment, dividing the number of collisions per segment by the flow per segment or the mean flow per ZAT segment.

We conducted these analyses using R [31] and its packages tidyverse [32] and sf [33]. We used QGIS for spatial data visualisation [34].

6. Physical activity analysis

Physical activity while commuting has potential significant effects on the health of commuters, as it promotes physical activity during the week. In addition, physical activity contributes to preventing and treating non-communicable diseases, such as cardiovascular diseases, cancer, hypertension and diabetes [35] and reduces symptoms of depression and anxiety [36]. For adults, WHO recommends 150 minutes of moderate or 75 minutes of vigorous physical activity, which translates into 500 Metabolic Equivalents (MET) per week for being physically active [33]. The intensity of physical activity is measured in METs. A MET represents the oxygen spent per minute performing an activity, increasing with vigorous activities and decreasing with sedentary activities.

We estimated the physical activity contribution through cycling and the health and economic value of the bicycle transport system in terms of preventable mortality. First, to estimate the contribution in METs for bicycle users in Bogotá, we estimated the average travel time per trip with the 2019 Mobility Survey and multiplied it by the METs per minute from the Compendium of Physical Activities (CPA) of commuting bike trips. The CPA compiles MET values for different activities that have published evidence, developed by Arizona State University and the National Cancer Institute [38]. We assumed that the average travel time per trip was the same in 2019 and 2020, as there is no updated information for 2020. We estimated METs at trip, person, and day level.

Second, the impact of the physical activity performed while cycling can be measured in terms of the economic value of mortality rate improvement through the Health Economic Assessment Tool (HEAT) [39]. HEAT is a tool developed by the WHO designed to conduct economic assessments of the health impacts of cycling [39]. The HEAT tool serves to estimate the value of reduced mortality that results from regular cycling. This tool is based on the best available evidence and transparent assumptions, making it easy to use with minimal data input requirements, adaptable to local contexts and scientifically robust [8]. The HEAT tool is designated to be used by professionals in different fields of knowledge, making it an integral and interdisciplinary tool for health and economic analysis.

We used the HEAT tool for assessing the health and economic value of reduced mortality resulting from regular cycling after the temporary bike paths were implemented during the pandemic in 2020 in Bogotá, compared to the pre-pandemic cycling patterns in 2019. As HEAT defines, the measurement can be performed only for members of the population between 20 and 64 years old. After estimating the input parameters for 2019 and 2020, the tool calculates the health and economic value of the bicycle transport system in terms of preventable mortality.

Appendix C. Causal Loop Diagram description and feedback loops description

Table 1 describes the feedback loops of the resulting CLD of the system. The first domain, civic culture, involves personal behaviours, civic culture programmes and norm appropriation that reinforce safe environments for cyclists. The second domain corresponds to cycling motivation. The internal motivators are supported through cycling groups accompaniment, whereas the external motivators are affected by the infrastructure, substitute transport modes and civic culture. The third domain corresponds to substitute transport modes. In this domain, the bicycle as the primary transport mode is impacted by the offer of substitute transport modes, which is reinforced by their quality and cost, compared to using a bicycle. The fourth domain corresponds to the quality of life, reinforcing cycling as a physical and mental health promoter. The fifth domain corresponds to infrastructure for bicycle use, in which road maintenance is crucial for increasing the use of the bicycle as a transport mode. Finally, the sixth domain corresponds to citizen participation. In this domain, women's cycling activism impels the visibility of cyclists, which leads to public policies for improving the mixed-used road network and bike paths and political power to react towards a pandemic with tactical urban health.

Table 1. Feedback loops description for CLD

Feedback loops	Description	Variables
R1	Reduction in bicycle collision rate due to drivers' behaviour towards cyclists. The rise in the use of bicycles improves the drivers' behaviour towards cyclists, reducing the bicycle collision rate, which increases the use of bicycles.	Bicycle use – Drivers' behaviour towards cyclists – Bicycle collision rate
R2	Increase in traffic congestion due to design of cycling infrastructure. The increment of bicycle use raises the cycling infrastructure design, which leads to an increase in traffic congestion, which impulses bicycle use.	Bicycle use – Cycling infrastructure design – Traffic congestion
B1	Reduction in bicycle use due to the increase of bicycle collision rate.	Bicycle use – Bicycle collision rate
R3	Increase of bicycle use due to external motivation for cycling. The rise of bicycle use leads to increased cycling infrastructure design and creates better cycling infrastructure connectivity. With these improvements, the travel cycling time reduces, generating more external motivation for cycling. These motives lead to a rise in bicycle ownership, increasing the use of the bicycle.	Bicycle use – Cycling infrastructure design – Cycling infrastructure connectivity – Travel cycling time – External motivation for cycling – Bicycle ownership
R4	Increase in external motivation for cycling due to the rise in the cost of substitute transport modes. The increase in the use of bicycles reduces the use of substitute transport modes, which increases the cost of those transport modes. Thus, the increase in the cost leads to more external motivation for cycling, which increases the use of the bicycle.	Bicycle use – Use of substitute transport modes – Cost of substitute transport modes – External motivation for cycling – Bicycle ownership
R5	Decrease in the use of substitute transport modes due to the increase in their costs.	Use of substitute transport modes – Cost of substitute transport modes
R6	Decrease in the use of substitute transport modes due to their quality. The reduction in the use of substitute transport modes reduces the road infrastructure design, reducing the utility of substitute modes of transport. This reduction leads to a reduction in the use of substitute transport modes.	Utility of substitute transport modes – Use of substitute transport modes – Road infrastructure design
R7	Increase in bicycle use due to the reduction in the use of substitute transport modes.	Bicycle use – Use of substitute transport modes
R8	Increase in bicycle use due to response capacity. The increase in the use of the bicycle generates a broader acknowledgement of social cycling organisations. This acknowledgement increases the political will towards cycling, which allows a better capacity to respond to a pandemic with tactical urban planning. In addition, this capacity favours the distribution of public space, which reduces bicycle collision rates and increases bicycle use.	Bicycle use – Acknowledge of social cycling organisations– Political will towards cycling – Response capacity to the pandemic with tactical urban planning – Distribution of public space – Bicycle collision rate
B3	Reduction in bicycle use due to public policies for improving road infrastructure. The increase in bicycle use generates a broader acknowledgement of social cycling organisations. This acknowledgement promotes public policies for improving the road infrastructure, which enhances the utility of substitute transport modes, reducing bicycle use.	Bicycle use – Acknowledgment of social cycling organisations – Public policies for improving road infrastructure – Utility of substitute transport modes – Use of substitute transport modes

Feedback loops	Description	Variables
R9	Increase in bicycle use due to improvement in road network maintenance.	Bicycle use – Road network maintenance
R10	Increase in bicycle ownership due to the acknowledgement of social cycling organisations. The increase in bicycle use raises the acknowledgement of social cycling organisations, which impulses bicycle ownership, increasing the use of the bicycle.	Bicycle use – Acknowledgment of social cycling organisations – Bicycle ownership
R11	Increase of bicycle use due to women cycling activism.	Bicycle use – Women cycling activism
R12	Increase in safety perception due to safer environments and civic culture. The increase in bicycle use foments the acknowledgement of women in public spaces, which promotes changes in cycling behaviours. These changes improve civic culture, increasing safe environments for cyclists and improving safety perception. This safety perception increases the use of the bicycle.	Bicycle use – Acknowledgment of women in public space – Change in cycling behaviours – Civic culture – Safe environments for cyclists – Safety perception
R13	Increase in the quality of life due to physical health. The increase in bicycle use promotes the improvement in physical health through physical activity, increasing the quality of life of cyclists and the use of the bicycle.	Bicycle use – Physical health – Quality of life
R14	Increase in quality of life due to mental health. The increase in bicycle use improves mental health, increasing the quality of life of cyclists and the use of the bicycle.	Bicycle use – Mental health– Quality of life
R15	Increase in mental health due to the reduction of traffic congestion. The increment in bicycle use promotes road network maintenance. The maintenance of the road network decreases traffic congestion, which improves mental health and bicycle use.	Bicycle use – Road network maintenance – Traffic congestion – Mental health
R16	Increase in bicycle use due to reduction in fear of using bicycles. The increase in bicycle use promotes the acknowledgement of social cycling organisations. This acknowledgement increases recreational and sporting cycling, which incentivises civic culture. Civic culture reduces the fear of using bicycles, which increases the use of the bicycle.	Bicycle use – Acknowledgement of social cycling organisations– Recreational and sporting cycling– Civic culture – Fear of using bicycles
R17	Improvement of civic culture due to public policies and culture programmes. The improvement of public policies for cyclists' welfare increases civic culture programmes, which improve civic culture.	Civic culture – Public policies for cyclists' welfare – Civic culture programmes
R18	Increase in norm appropriation due to development of public policies for cyclists' welfare.	Public policies for cyclists' welfare – Norm appropriation
B2	Improvement in safety perception due to cycling groups accompaniment.	Safety perception – Cycling groups accompaniment
R19	Increase in intrinsic motivation for cycling due to cycling groups accompaniment. The increase in bicycle use increases the cycling groups' accompaniment to other cyclists, which improves the intrinsic motivation for cycling and increases the use of the bicycle.	Bicycle use – Cycling groups accompaniment – Intrinsic motivation for cycling

Feedback loops	Description	Variables
R20	Increase in the distribution of public space due to road network design.	Road network design- Distribution of public space
B4	Reduction in bicycle use due to reduction in traffic congestion. The increase in bicycle use leads to better road network maintenance. This maintenance reduces traffic congestion, which reduces the use of bicycles.	Bicycle use- Road network maintenance – Traffic congestion

Two of the most relevant feedback loops are reinforcement loops 3 and 12. Reinforcement loop 3 shows that the rise in bicycle use leads to a better design and increase in cycling infrastructure and improves connectivity. With these improvements, cycling travel time reduces, motivating more cycling trips. This motivation leads to a rise in bicycle ownership, increasing bicycle use. The reinforcement loop 12 shows that the increase in bicycle use recognises women in public spaces, thus promoting changes in cycling behaviours. These changes improve civic culture, create safe environments for cyclists, and improve safety perception. A better safety perception increases bicycle use.

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Complex systemic failures in the Edinburgh Schools case

By Prof Jonathan Gosling, Prof Mohamed Naim, Prof Bill Hewlett, Stewart Macartney

Executive summary: In January 2016 an outside cavity leaf wall collapsed at Oxgangs Primary School during a storm, leading to wider school closures, disruption to learning, and widespread concerns about safety. Based on publicly available documents, the experience of the team, and academic frameworks, a retrospective analysis is undertaken. The failure was a consequence of deeper systemic issues, as well as assumptions about complexity. Changes are recommended in the areas of building standards, training, independent verification, collective sensemaking and 'self-reflective practice' by stakeholders and clients.

Tags: education infrastructure, building failure, wall collapse, mason wall-ties, construction quality control and regulatory compliance, fragmented procurement and supply chain, systems engineering change model, cynefin, cause and effect analysis, United Kingdom

Section 1: Background and introduction

In January 2016, an outside cavity leaf wall collapsed at Oxgangs Primary School when Storm Gertrude hit Scotland, leading to school closures, disruption to learning and widespread concerns about safety. Approximately nine tonnes of masonry fell at the school during the storm, leading to closures at Oxgangs, but also wider school closures to a further 16 schools for a period of months for investigation, structural surveys and remedial work. All these buildings had been built as part of the same Public Private Partnership contract with Edinburgh Schools Partnership Limited (ESP). The consequences were time and cost resources for remedial work, as well as disruption to children's education and communities. Luckily, there were no injuries or deaths, but this was purely a matter of luck as the collapse happened out of regular school hours. In addition, in the wake of the collapse, an initial BBC report revealed that 72 more schools in Scotland were found to have similar defects and judged to be unsafe (BBC, 2017).

The most obvious technical cause of the collapse of the wall was defects and poor-quality construction in the building of the wall. It was later found that it had failed to achieve the required minimum embedment for wall ties. However, as we will show in the case analysis, this failure arises from a combination of many deeper causes, exacerbating factors and assumptions. As was noted in the BBC's report, the failure was not a case of one or two rogue builders, but a consequence of much deeper systemic issues (BBC, 2017).

The Edinburgh Schools case is important for several reasons. The first is that it was 'avoidable'. An independent inquiry concluded that the failure was indeed 'avoidable' (Cole, 2017), since with better practices, designs, processes and approaches, the failure would not have happened. Secondly, it is not a single isolated type of event, and gives insight into a broader and more general problem. The interweaving failures in assumptions regarding complexity, minimum building standards, quality culture, oversight and commercial drivers established during the early phases of the project are likely recognisable across many building sectors and programmes of work. Thirdly, in the wake of the Grenfell disaster, building standards and quality failures are currently high-profile concerns. We consider that the case gives an insight into the way in which systems thinking can be used to approach such issues differently.

Based on a range of publicly available documents, and the experience of the team, we will analyse the stages of the lifecycle of the Edinburgh Schools case from original planning and design, through build and handover to post-construction operation. Taking the generic temporal phases of construction as a starting point, we structure our analysis based on an academic change model to classify the foci of activities and failures as being primarily of technology, process, commercial and attitudinal. In addition, to better understand the nature of systemic cause and effects in the case, we apply complexity frameworks to give generic insights into suitable management approaches. The analysis of the Edinburgh Schools case demonstrates how prevailing assumptions of simplicity in complex systems can lead to chaos and has potential for disastrous outcomes.

In the case analysis, we use and apply an existing sensemaking framework, named Cynefin, which is a classification that allows understanding of the 'habitat', or 'cynefin' in Welsh, within which the project is perceived to exist. **Figure 1** shows its domains. Cynefin classifies contexts that we may find ourselves in, in terms of Ordered, Simple and Complicated, and Unordered, Complex and Chaos. These domains have very different characteristics, especially in terms of the assumptions about the nature of cause and effect, and so it is evident that different managerial approaches are needed.

A common issue is that studies and tools and techniques tend to assume projects exist in a predictable world of cause and effect where things go according to plan. This often proves to be wrong, and chaos ensues. Our key message, however, is that management methods suited to a predictable domain are not wrong in themselves, but that they become so when applied in an inappropriate context, the unordered (complex) domain as Cynefin terms it. On this basis, a key message is that management methods or styles are not so much 'wrong' as 'wrong for their domain', so identification of the domain becomes critical for success. To determine which domain that we are 'in', the implication of which is to give a basis for agreement on the appropriate management methods and styles, usually requires an element of discussion, discourse and ultimately agreement or consensus among different stakeholders. Hence, we may actually find ourselves in a fifth disorder domain, where there is no shared understanding of which of the other four domains that we are in. If used effectively, the sensemaking framework can help to develop a shared understanding of the types of problems faced, their causes and solutions, agreed goals and targets, and identification of the appropriate problem-solving tools. Most importantly, it facilitates the 'right-sized' management tools, techniques and interventions for the specific situation faced, as well as self-reflection on our assumptions, helping to make them explicit.

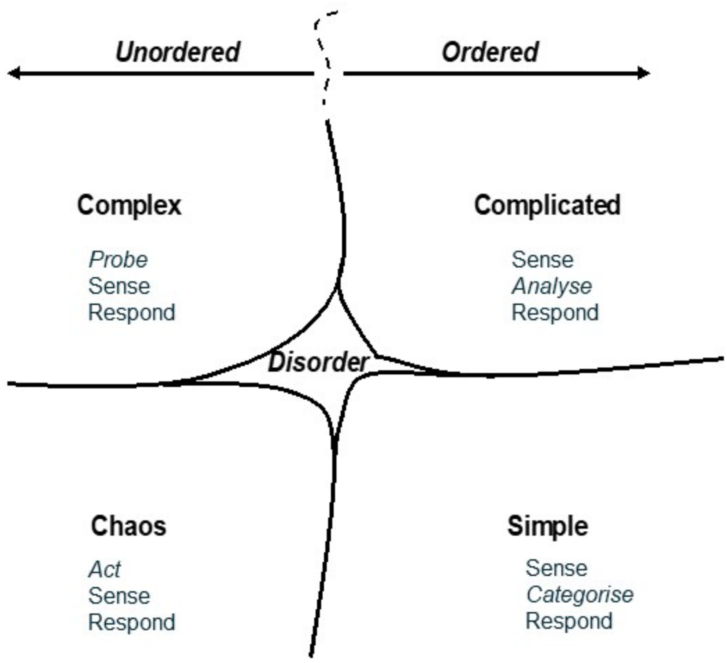

Figure 1: The Cynefin Sensemaking Framework (Kurtz and Snowden, 2003; Snowden and Boone 2007).

Building on a long line of research, Towill (2001) proposes a systems engineering toolkit to approach systems change. This consists of addressing four interacting systems change levers (see **Figure 2**). Here the constituent elements are technology, attitudinal, commercial and process changes. While there is often overlap, it is often possible to identify one or two primary change drivers. An integrated approach to systems change is proposed, but interestingly and highly relevant to our case, Towill argued that the changes count for very little unless a total quality management (TQM) culture is established throughout the supply chain. We utilize both of the above frameworks for analysis of the Edinburgh Schools case study.

Section 2: Analysis and insights

Complexity and the project stages

Figure 3 shows assumptions, misperceptions about complexity, and the shifting situations through project phases at Edinburgh schools. The initial and primary focus of the Edinburgh Schools inquiry was the failure of the cavity wall construction, so we focus on those elements, albeit in their wider context, as we analyse the project stages.

Planning and design

Early planning for construction work began in 1998 when the City of Edinburgh Council submitted an

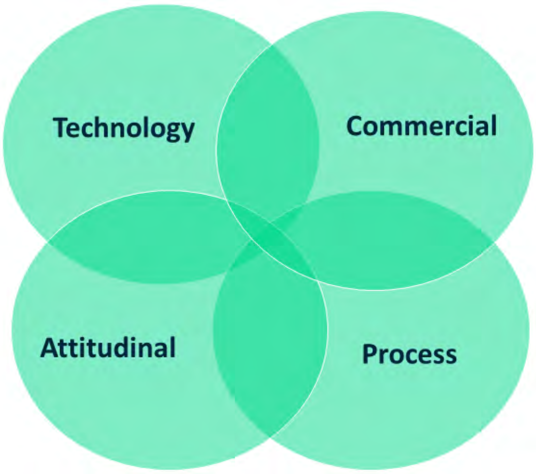

Figure 2: Systems Engineering Change Levers (Towill 2001).

Outline Business Case in support of a bid for revenue funding for a proposal to upgrade its Schools Estate through a Public Private Partnership (PPPI) model. The Full Business Case was approved in 2001. Responsibility for the design and construction of the schools was sub-contracted by ESP to a joint venture company formed by the Main Contractor and Facilities Management Company (AMJV). AMJV appointed two architectural firms and an engineering consultancy to undertake responsibility for the structural design of all 17 school projects. Tier 2 construction contractors effectively became sub-contractors to AMJV. Hence, the architects and engineers on the PPPI had no direct contractual relationship with the contractors employed to do the work and instead reported to AMJV. Furthermore, there were a large number of contractor-designed elements, rather than being made by the appointed engineers and architects, leading to split design ownership and lack of understanding (clarity?) of roles and responsibilities. Not long after the wall collapse, there was speculation as to whether PFI (sub-contracting?) arrangements push quality and design considerations to the margins, possibly emphasising economic drivers over wider public value, as well as separating designers from the responsibility to inspect their work (Marrs 2016).

At the design phase, the technological solution would have ranged from simple to complicated, bearing in mind that standards and systems exist for such solutions, even in non-standard locations. A structural engineer designed the structure taking into consideration the stability of masonry wall panels to ensure that they could withstand wind loadings arising from wind-speeds and loadings as currently prescribed in British Standard BS EN 1991-1-4: 2005 for use with PD 6697 2010, (BS 6399 applied at the time

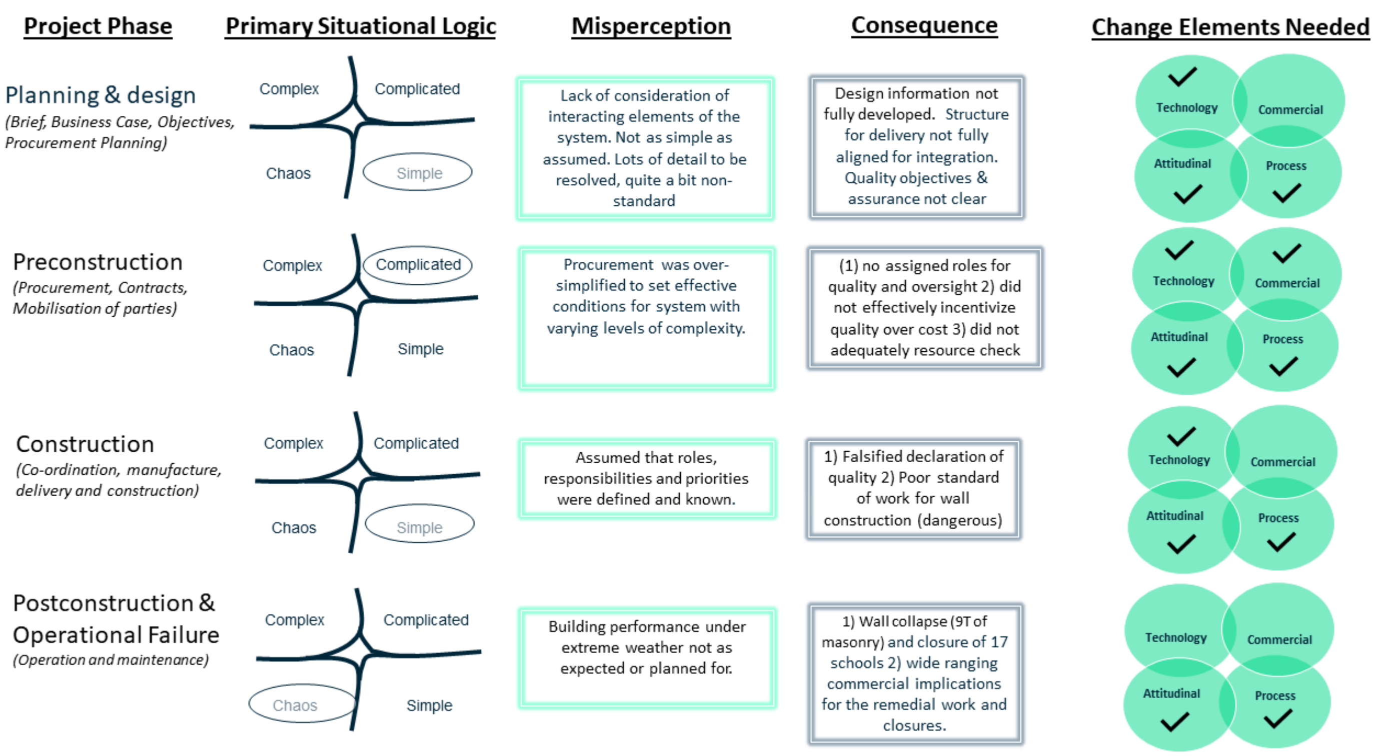

Figure 3: Analysis of project phases at Edinburgh Schools using Cynefin and Change Levers.

of the design of the PPP1 schools). Both standards take account of location, topographical exposure and orientation. Designs were 140mm inner leaf and 100mm outer leaf of either brick or rendered block. Some masonry panels had bed-joint reinforcement (BJR) specified for every course, some specified for every second course, and some unreinforced. Some were specified with wind posts as well as BJR. Investigations showed that many panels that should have had BJR had none, which dramatically impacted the strength of panels.

Cole (2017) points to a few issues at the planning and design stage. First, the structure allowed for key organisations to become one or two steps removed from each other, so that no proper relationship existed. This was the case between the designers, client, joint venture, and other contractors. Secondly, during the development of the brief, the quality objectives and approaches to ensuring quality could have been clearly defined at an early stage. A key misperception at this stage was the extent to which interactions (or lack thereof) between different elements of the design and delivery (organisational and technical) would simply work effectively without the right structures or provision in place. This led to design information not being fully developed, the structure for delivery not being fully aligned for integration or the delivery of quality objectives. An important misperception relating to the planning and design stage was the assumption that responsibility for elements and outcomes of the system, which were highly interdependent and complex, could be passed along layers of subcontracts without oversight. Changes to processes, attitudes and technology for design information are needed.

Preconstruction

During preconstruction, all formal communication to the Tier 2 contractors from the design team members in relation to the design and construction of the Phase 1 PPP1 schools, including drawings, specifications and technical requirements, had to be channelled through, approved and issued by design managers and project managers directly employed by AMJV. An Independent Certifier was appointed, but as noted by Cole (2017), quality assurance planning and procedures could have been clearer and there was no resource, requirement or provision for a Clerk of Works. Tendering processes are well known to be prone to opportunistic behaviour, especially when structured through layers of subcontracting, and a lack of design specificity at tender stage exacerbates the potential for error. A recognition of this complexity would suggest that arrangements to check outputs, skill levels and competency were as anticipated and the nuances of the work appreciated. Hence, during the preconstruction phase, procurement was oversimplified, and did not consider the interdependencies between elements and the drivers of different behaviours. For instance, for the procurement of masonry accessories, some were free issue and some were to be procured by the sub-contractor. This led to a lack of assigned roles for quality and oversight, did not effectively incentivise quality over cost, and did not adequately resource quality assurance. All four change drivers are needed to address issues during this phase.

Construction

Construction work took place during the early 2000s with schools in PPP1 beginning to be completed in 2004. Following a first phase of 13 projects, Oxgangs School was one of a second phase of four PPP1 projects completed in February 2005. These were constructed by Miller Construction, acting in the role of a Design and Build contractor. Cole (2017) notes that during the period of construction there was a general misconception as to the extent and purpose of site inspections undertaken as part of the Building Standards system. While visits to the PPP1 schools were undertaken by building officers, these were primarily focused on drainage checks. Key issues can also be identified in the overall coordination of the supply chain, and accessibility of design information to trades and subcontractors. This particularly applied to bricklayers and site supervisors. Although the construction of the cavity wall itself should be regarded as simple, two key factors highlighted by the report that contributed to the deviation from standards were the lack of design information by which the brick layers could have determined the depth at which the ties were set into the leaves and the payment mechanism for the brick layers (Cole, 2017). There was also poor coordination of information and details between architects' drawings and engineers' drawings with some conflicting information, leading to confusion. Hence, during the construction phase, there was an assumption that roles, responsibilities and priorities were defined and known. In particular, responsibility for checking and verifying standards slipped between the gaps. Full availability of information was not accessible at all times. This led to a falsified declaration of quality and poor standard of work for wall construction. Changes to processes, attitudes and technology for design information are needed.

Postconstruction and operational failure

Following the wall collapse, council officers closed the school with immediate effect, and structural engineers were appointed to provide advice relating to further risks to safety that might be associated with the collapse and possible remedial work. A visual inspection and report on the external walls of all 17 PPP1 projects was also requested. Subsequent inspection and analysis identified a combination of excessive cavity width, related non-verticality and incorrectly constructed wall ties, missing BJR and wind posts, missing wall head restraints, as well as panel edge ties back to primary structure and columns. This resulted in a cavity wall construction in which many of the ties had insufficient embedment in the outer leaf.

This represents chaos in the immediate aftermath of the collapse: What are the implications of the collapsed wall? What do we do? The second follows rapid intervention by the City of Edinburgh Council, which closed the School, transitioning the situation (at least as far as the authorities were concerned) into the Simple domain. There then followed an interesting period (Disorder) during which there was no consensus on the severity and urgency of the situation. During this period, the school remained in use, but subject to expert structural monitoring and a constant weather watch (a Complex arrangement for structural engineers; Chaotic for teachers who had to work around these unsatisfactory arrangements; Simple for pupils (the school was open, get on with it and do as you're told), and Complex going on Chaotic for contractors who had to recognise they had a problem with unforeseeable potential outcomes. Meanwhile the City Council, school governors and staff, contractors and structural advisors sought consensus on what to do and how, constantly abated by parents and the press). Following this, a further phase, which began as Complex but later became Complicated, during which Oxgangs and the 16 other schools within the same PPP programme were investigated, closed or partially closed and remediated; continued until August 2016. Accomplishing this involved bussing pupils to different locations and redeploying staff accordingly – an exercise at the limit of what can be defined as complicated. Process and attitudinal changes are needed to drive change.

Causes, consequences and exacerbating factors

Figure 4 shows causes, consequences, outcomes, exacerbating factors and controls.

Causes and exacerbating factors

The diagram highlights two primary and underlying causes, both

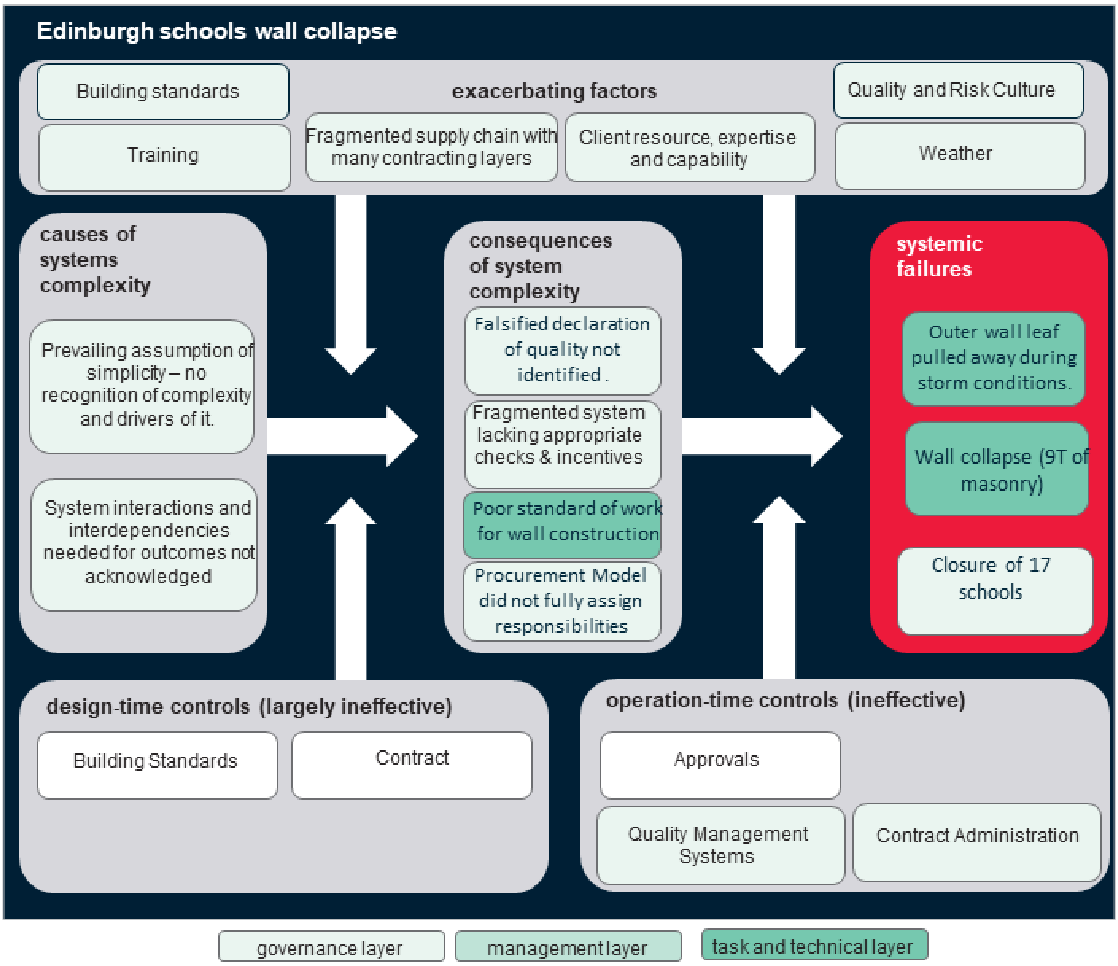

Figure 4: Analysis of causes, consequences, outcomes, exacerbating factors and controls.

related to 'mindset' at the time of the project. Firstly, the assumptions relating to complexity. A range of aspects across project phases were oversimplified, so that solutions for a 'simple situation' were applied (Naim et al., 2021). Oversimplifying left design details unfinished and responsibilities unassigned. Secondly, the picture that emerges from the project phase analysis presented in figure 3 is that a series of omissions, oversights and assumptions gather and creep towards large scale problems. From the outset, these interactions and interdependencies were not adequately considered. As noted by a commentator at the time:

> *"There are systems in place that are supposed to pick up these issues going through – but that relies on everyone in the chain to do what's expected of them. And when things get missed, that can have an impact further down the chain, and ultimately I think that's part of what's happened here"* (BBC, 2017).

Through early planning and procurement, assumption about drivers of behaviour and quality standards were made, which cascaded through the design phase, where designs were not fully detailed or accessible, and into mobilisation phases, where interface issues arose, collaborative links were not formed, and an environment formed in which poor construction work could pass through unchecked. Ultimately, bricklayers did not follow process or adhere to standards, and the checkers did not conduct effective verification.

There are a range of exacerbating factors, which inflamed the above issues. Building standards are often treated as minimum standards, and the standards articulated in design are often separated from the administration and management during the construction phase. Supply chains are typically based on short term or one-off relationships in the construction industry, leading to fragmentation. This is exacerbated by layers of subcontracting. In addition, sadly, the quality culture that is seen across some areas of the manufacturing sector (based on Total Quality Management) is very often not replicated across the construction sector, where quality is often perceived as someone else's responsibility to check. Client resource and expertise may also have been a factor in terms of monitoring and control, but also assigning responsibilities and managing the overall programme. Finally, the weather: the wind speeds in Edinburgh on the day of the collapse were high, but not in excess of design expectations.

Consequences and systemic failures

The City of Edinburgh Council, in common with the majority of other public sector clients undertaking PPP projects for the first time, oversimplified the procurement process, for example by not appointing Clerks of Works to provide inspection services. The public procurement conditions did not establish the right incentives for a safety or quality culture to flourish. Economic decisions by the contractors were focused on small savings and commercial incentivisation of bricklayers, based on the number of bricks laid rather than on the value of work done; bricklaying is more complicated than simply 'laying bricks', and value will not be achieved if perimeter fixing details, and various mid-panel details, are not installed correctly. This led to perverse incentives, encouraging the omission of elements providing the essential structural integrity of walls. The failure to incorporate the ties, restraints and joint reinforcements, in accordance with the design, impacted significantly on the capacity of the panels to resist the required levels of wind-loading and undermined the integrity of the structural design of the external walls of the schools. The PPP1 contract contained a requirement for the preparation, provision to the council and maintenance of as-installed drawings and related documentation. This provision was not adequately complied with. Guarantees of adequate quality were also false. Checking and administration of standards was disjointed.

Section 3: Discussion and transferable learnings

What went wrong? What should have been done differently?

Section 2 highlighted a wide range of factors that interacted and led to the wall collapse. From the analysis of project phases in section 2a, it is possible to see the gradual build up and knock-on effect of omissions and assumptions as they cascaded through the project phases. Through the systems analysis of causes and consequences in 2b, it is possible to see that project failings were also positioned within a particular context, whereby they were inflamed by a range of exacerbating factors and underlying assumptions.

Design and operation time controls should have addressed these failings and issues more effectively across the project phases. A better level of detail in the design drawings would clearly have helped, but this prompts some interesting discussion points: What level of detail was needed in the design drawings? How should the level of design detail have been verified? How could overlap between architectural and information shown on architects' drawings and information shown on the engineers' drawings have been managed and integrated? Controls to improve collaborative structures between clients, designers, contractors and subcontractors, so that organisations are not removed through many decoupled layers, and better integration of the supply chain, would have helped to clarify roles and responsibilities and develop more proactive information sharing mechanisms. A clear area where system controls would have helped avoid the failures is the clarity and articulation of a strategy and process for independent oversight, checks and verifications at different levels. How should work in accordance with the design, and accepted good workmanship, have been verified?

What can the industry learn from the Edinburgh Schools case? What are the broader transferable lessons?

Following the independent inquiry into the Oxgangs school wall collapse, a broader review of building standards was undertaken in Scotland (Cole 2018). This latter review found that Oxgangs did indeed represent non-compliance with the requirements of the Scottish Building Standards and suggested that steps were needed to strengthen adherence. In particular, there is a need for verifiers and applicants to fully understand and deliver on their responsibilities. Cole (2018) points towards culture change through education and training as a key area for change. A related area, which Cole (2017) alludes to frequently in the independent inquiry, is the value of experienced Clerks of Works, an area of expertise that will need to be cultivated and promoted through training if they are to be used properly in the future. However, even with these changes much work is required to foster the Total Quality Management culture seen in other industries.

A key implication of our preceding discussion on the Cynefin complexity domains and the systems engineering change levers is the importance of collective sensemaking by stakeholders and clients to avoid making overly simplistic assumptions. The desire for situations to be determinate and simple, so that spreadsheets, documents and plans can be drafted with certainty is understandable, but this is often unachievable in practice, so governance approaches and incentivisation models must reflect that. A broader lesson to be learned, therefore, is the importance for leaders and teams to routinely examine and reflect on their assumptions at critical decision points. Such 'self-reflective practice' to explicitly articulate assumptions, and develop any potential mitigation plans, can be encouraged through the project governance processes. For instance, through assumption mapping at the planning stage, monitoring and control processes as the project progresses and then project learning logs and retrospectives to better understand the impact of assumptions made. An interesting discussion point is that decisions are often taken without their criticality being realised at the time, therefore the mindset for self-reflection needs to be cultivated. This could also be anchored within the project phases of planning, design, construction and operational and maintenance, as per **Figure 3**. In doing so, we hope that designers and contractors think beyond small, scoped packages of work and completion of a project, towards broader longer-term value.

Some concluding thoughts are offered via a summary of necessary changes required with references to the change levers discussed earlier in the case:

- <u>Process</u> – changes are needed in the procedures to assign responsibilities for oversight and independent verification, as well as mechanisms for accessibility of up-to-date and detailed design information. Conditions of engagement, as set out in the procurement strategy, would be better articulated to align the roles of the various supply chain actors. Process improvements could also be facilitated via design checklists and responsibility matrices for design and construction. In addition, formal gateways and review stages in building standards within the process, which also prompt leaders and teams to make their assumptions explicit, would help control safety critical works.
- <u>Commercial</u> – reform is needed to align economic incentives and drivers with project aims, taking into account complexity and uncertainty as project phases progress. Deeper understanding of the behavioural implications of procurement decisions on trades and contractors, as well as site activity, is needed.
- <u>Technology</u> – new digital technologies provide new opportunities for open access and standards for designs. Alternative forms of construction, with greater offsite use, may reduce the possibility for human error. Offsite approaches are becoming a major focus due to the ability to verify system elements, offer better quality control and working environments, as well as address labour and skills shortages. However, this needs to be balanced against the risk of fragmentation of procurement, increased criticality of element interfaces, and alternative modes of systemic failures inherent in new technologies.
- <u>Attitudinal</u> – broader changes are needed to reconsider assumptions regarding simplicity and complexity, so that planning and procurement strategies devote due acknowledgement of complexities and the risks and implications flowing from it. Further attitudinal changes are required for a positive quality culture to thrive, and finally changes to assumptions about the nature of interdependencies, particularly through better

adoption of supply chain integration practices. A greater level of self-reflection and examination of assumptions at critical decision points is needed, leading to more explicit articulation of premises relating to complexity and corresponding mitigation plans. Training will likely play an important role, at the level of leaders and teams, but also more specifically targeted at bricklayers and trades so that there is an increased awareness of technologies and the broader safety implications and impacts of work undertaken, as well as expected values and behaviours.

This case study has provided a retrospective analysis of a project with significant failure. It is important to look back and learn from such events. Many industries are now using a 'manage by projects' approach and it is possible to see from the Edinburgh Schools case that there is a shifting landscape through complexity domains as the project proceeds and problems build though interdependencies. Occasionally, problems will align in such a way that a critical failure arises. A mixture of attitudinal, technology, commercial and process-based system changes can minimise the potential for this to happen, but this needs input from professional communities of practice, standards, as well as education and training. It also needs a willingness to be self-reflective and examine our assumptions at critical decision points and we hope that this case provides guidance for doing so. Given the depth of impact of some of the exacerbating factors discussed in the case (for example fragmented supply chains with layers of subcontracting focused on short term costs), there is a need to understand the systemic nature of the problem, which we hope has been highlighted in this case, and then develop a systems-based response to drive system actors and behaviours towards the desired outcome.

How using the Cynefin framework and systems engineering approach helped us to analyse the problem

Finally, we offer some reflection on the value and utility of the Cynefin framework in helping to illuminate the problems in the case, and how it might help in other situations. In the case, we used the Cynefin domains to show a changing landscape as the project phases drifted in and out of situations with different characteristics and any misperceptions observed. A key distinction made was the cause-and-effect chain for different contexts: cause and effect are relatively stable in the simple domain and then get less stable in other areas of the framework and the differences call for different and appropriately tailored management approaches. Retrospectively, it is possible to observe fundamental misperceptions of those involved in the case seeing some situations in the system as simple when there were elements of complexity to be managed.

The Cynefin framework probes and surfaces assumptions relating to changing situations, as well as providing a language to articulate them. This, in turn, helps to challenge deeper habits and mindsets and to offer a basis for preparing a response to situations. It is possible that we can never fully know with certainty all elements of the system and we argue that there is a risk of oversimplifying and not developing system capabilities and mitigation and contingency plans for less predictable and/or uncertain elements. Embedding the Cynefin approach into planning and monitoring processes will help teams to sense make and articulate their assumptions and plan appropriate responses. The systems engineering change levers adopted in the analysis of the case provide a practical categorisation of possible initiatives and actions. We encourage considerations of complexity, process, commercial, technological and attitudinal to be explicitly addressed in risk assessments and project management processes.

Further reflections and lines of enquiry

The lack of training, education and understanding of the significance of the masonry accessories by the bricklayers was an important cause of the failure. Unless that is addressed, no amount of systems or checks will address fundamental effective ownership of quality. Quality must start with those doing the work, but how can training be effectively embedded?

Safety critical elements and items must be treated, checked, monitored and verified. However, effective verification is a major challenge. What records are needed and how should they be obtained to ensure and demonstrate compliance?

Product specification, standards and quality requirements often contain conflicting information, specifications and inconsistent levels of detail. How should safety critical components be specified, detailed and communicated at all levels?

Many sub-contracting organisations have questionable quality systems. Reliance is often placed on the quality management systems of the principal contractor. This fragmentation, and misunderstanding about the nature of quality management, often leads to quality being a burden or cost to be passed along. What types of contractual relationships, contracts and metrics are needed and which procurement strategies can best support quality improvement? How can a Total Management Culture be successfully embedded in the construction industry?

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Systemic failures in nursing home care

By Prof Joachim Sturmberg, Dr Len Gainsford,
Prof Nicholas Goodwin, Prof Dimity Pond

Executive summary: Poor care and poor outcomes are a ubiquitous problem in nursing home care. We developed – based on findings in the literature, personal experiences in nursing home care and interviews with core stakeholders – a 3-D system map to represent the structure and the dynamic links within the system. It showed that the system is highly fragmented, dysfunctional and without any evidence of system leadership and transparency of system governance and accountability. The system requires a fundamental redesign – the approach to redesign is illustrated and can serve as a blueprint.

Tags: preventable morbidity and mortality, health case, aged care, causal loop diagram, regulatory and governance failure, financing failure, workforce shortage and skills, vulnerable population, system redesign, Australia

Section 1: Background and introduction

Individuals in nursing homes are a highly vulnerable group of usually frail and/or cognitively impaired elderly members of society. They are at a very high risk of adverse events such as falls and infections and outcomes (for example malnutrition, fractures, skin ulcerations or delirium) and hence require interdisciplinary care from highly skilled and motivated health and social care professionals.

The 'residential aged care' sector – the government's preferred term, although residents and their families largely prefer the term 'nursing home' – has a long and well-documented history of failings [1-8]. Aged care in most western countries is a government responsibility, it is for government to make the necessary systemic changes to achieve a well-functioning care system for frail elderly people who can no longer care for themselves.

Multiple investigations and inquiries have repeatedly shown the same – systemic – reasons for the sector's failings – insufficient funding, privatisation, inadequate governance with a process rather than outcomes focus, lack of responsiveness to often rapidly changing resident needs due to understaffing, inappropriate staff mix and inappropriately low staff skills. However, these insights have not resulted in any meaningful systemic changes to the 'aged care system'. More disturbingly, as the three cited reports and inquiries [2, 7, 8] have highlighted, the changes to specific parts of the system have in many cases worsened the failings in nursing home care. The (inept) actions of government have ultimately contributed to the unnecessary and unacceptable suffering of older people in nursing homes who were already one of the most vulnerable groups of people in our communities.

To understand these failings, one needs to understand how systems operate. The system of aged care should be seen as a continuum from those services designed to support older people living independently at home through to supported living in voluntary retirement villages, and other forms of serviced accommodation, onto nursing home settings that offer higher levels of care and support to the more dependent – the 'aging in place' strategy (**Figure 1**). Our report specifically focuses on the nursing home setting and its systemic failings.

A whole-of-system perspective

The nursing home system can be described as a socially constructed and hierarchically layered organisational system. It is a complex adaptive system (CAS) given its highly dynamic networked interactions. The function of any organisational system arises from four key attributes – the organisation has articulated its 'purpose', has set itself a limited number of 'specific goals to achieve', and has agreed upon a set of 'core values'. These are the foundation from which the fourth attribute of an organisation arises, its collectively defined – typically – three to five 'simple (or operating) *rules*', the rules that determine the internal and external interactions among its members (the culture of the organisation). Hence, the nursing home system might best be described as a *Complex Adaptive Organisation* (**Figure 2**).

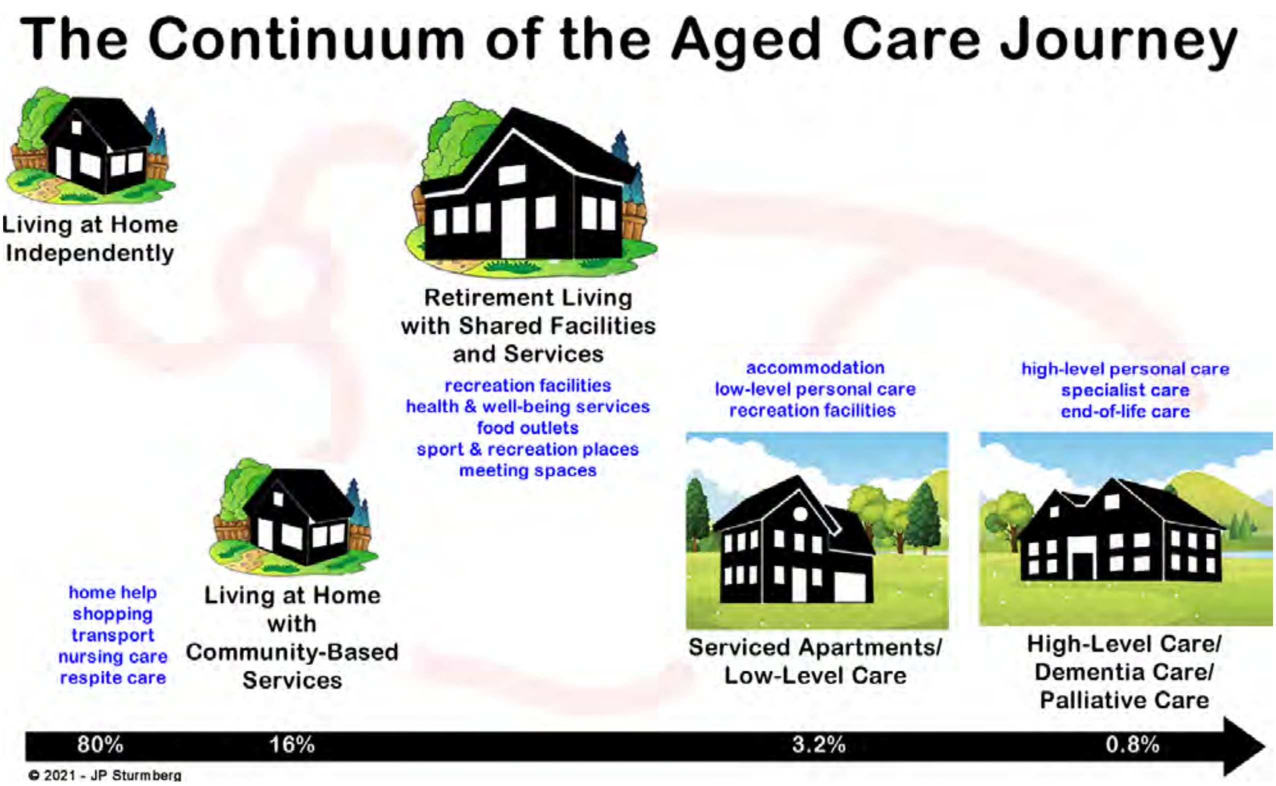

Figure 1 – The aged care journey – "aging in place". Note: only about 0.8% of the total community will ever require nursing home care across their lifetime

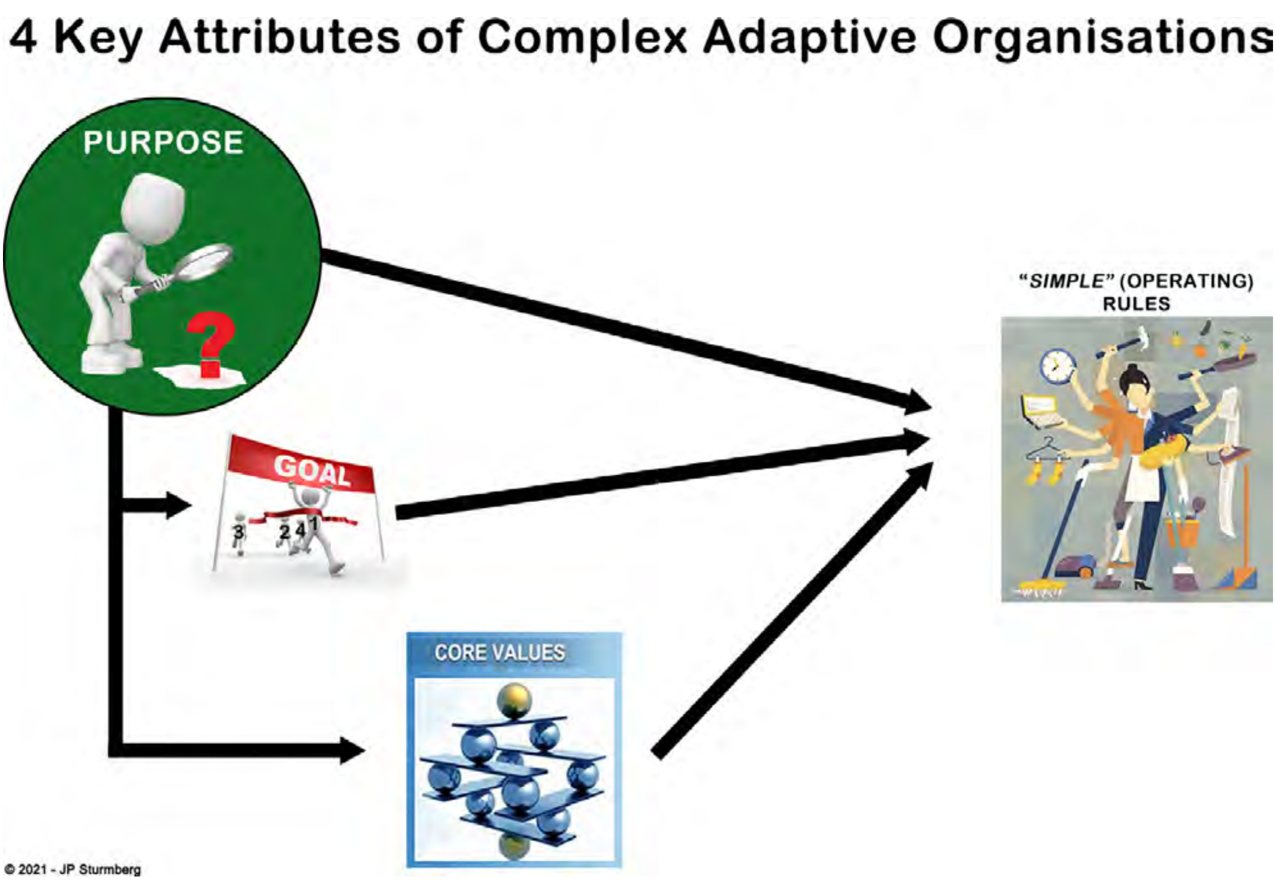

Figure 2 – The Key Attributes of a Complex Adaptive Organisation

The effective, or seamlessly integrated, functioning of a complex adaptive organisation depends on all its members at all levels of the organisation's system, working collectively towards the realisation of its purpose. The purpose provides the necessary focus that allows its members to adapt to the inevitably emerging challenges within the organisation in its operating environment. It is the primary task of an organisation's leadership to maintain everyone's focus on the defining common purpose [10], and to ensure that all its members have, and utilise, the required resources to achieve its specific goals.

In addition, the capability of a complex adaptive organisation to meet its purpose is governed by top-down causation [11]. In other words, the nursing home system's 'function' is based on 'top-down causation' that 'enforces' the bottom-up work that needs to be done. Top-down causation relies on higher levels passing on information that (a) conveys what work should be done and (b) limits the possible ways it can be done. Information that too tightly constrains fails to provide the necessary information for any work to be done (for example to meet the specific needs of the local context) while information that too loosely constrains does not clearly enough convey what work needs to be done and so potentially leads to a divergence from 'purpose' [9].

Translating this into the nursing home system allows us to construct a multi-level interpretation of the system as a complex adaptive organisation (**Figure 3**).

Section 2: Analysis and insights

The <u>government level</u> (government, as defined by the *Aged Care Act* 1997) seeks to keep the system's focus on its key purpose (meeting the care needs and aspirations of the frail elderly and maintaining their dignity) and the provision and enforcement of instructions of behaviours the agents of the system have to adhere to.

In addition, the top layer also has to provide the required resources to the lower levels so they can do the work that needs to be done and ensure – through a regulatory agency – the accountability and governance of the system.

The <u>proprietor level</u> provides the physical infrastructure of a nursing home as well as employing the necessary staff to deliver the required care. It is the related <u>facility management level</u> that is responsible for implementing care and monitoring the quality of the work done – in particular, it is the role of management to constantly adapt resource allocation (physical and staff) to the constantly and often rapidly changing care needs of individuals.

The <u>care team level</u> delivers the needed care, but also aims – within the limits possible – to stabilise and/or minimise disease burden and prevent health risks arising from a person's frailty. Staff members also have responsibility for identifying and mediating their own knowledge and skills gaps.

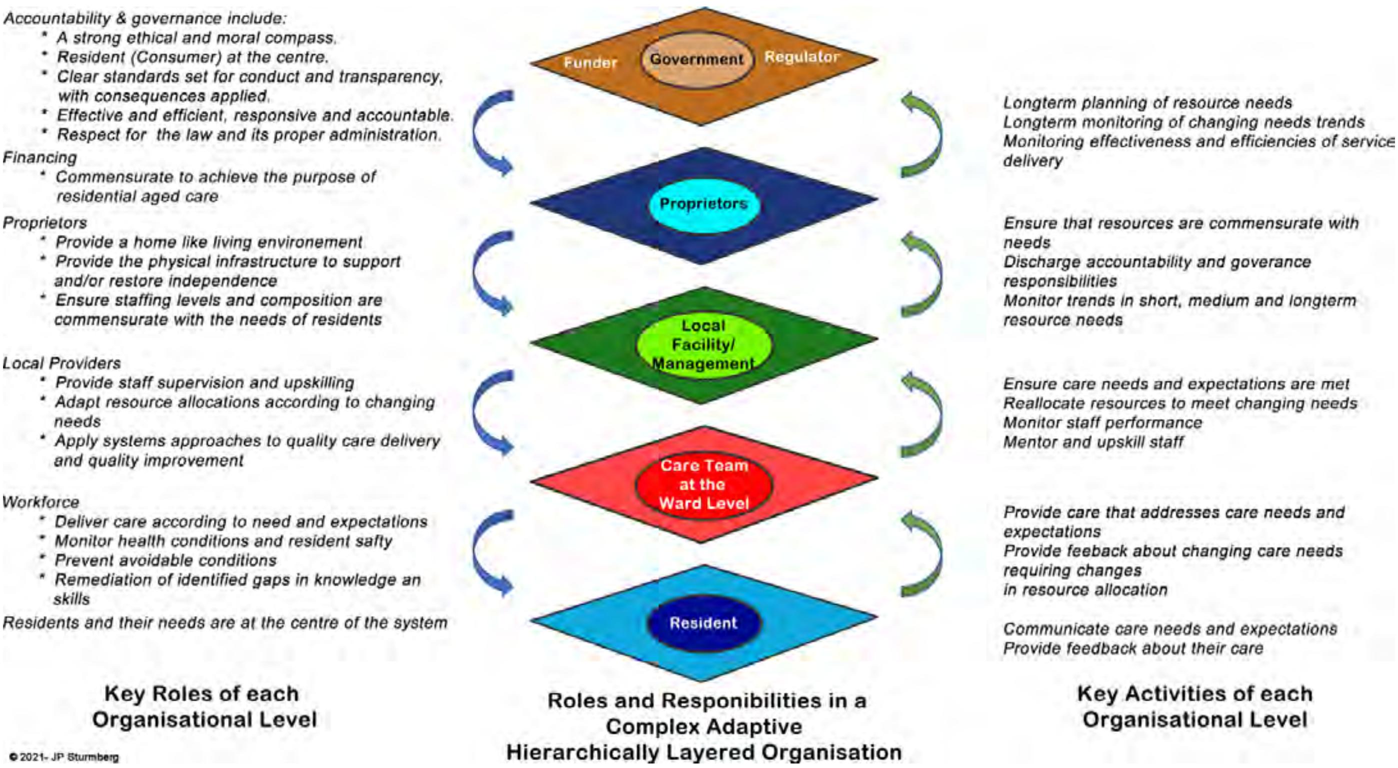

Figure 3 – Roles and responsibilities within the nursing home system as a complex adaptive organisation

At the resident level, every resident (and their family members) will provide input about the care needs that need to be met by care staff.

The observed functioning of the nursing home system, as a complex adaptive organisation, emerges from the bottom-up based on a complex interplay of feedback that represents the ever-changing requirements to achieve the outcomes defined by the organisation's purpose (**Figure 3**). Hence, residents will provide input about their care needs which must be met by care staff. Care staff in turn need to communicate the changing needs of each person to ensure the adaptive provision of physical and workforce resources. It is for the nursing home's management to provide required resources, but also to ensure these are applied in the most effective, efficient and equitable way without compromising care outcomes. In addition, management needs to ensure that staff members are mentored and upskilled where needed so as not to endanger the quality of care, or worse, threaten people's safety.

Proprietors are ultimately responsible for ensuring the quality, effectiveness, efficiency and safety of their facilities. They must both ensure accountability and governance requirements are met and advocate that funders provide the required financial resource to achieve the system's purpose. Their feedback allows overall forward planning of policy and financing frames at the government level to maintain the overall 'nursing home system' focused on achieving the system's purpose – to provide individuals with care that meets their needs and maintains their dignity.

Only seamlessly integrated, purpose-focused organisations can consistently deliver the desired outcomes as they understand them, paraphrasing Drucker [12], how to "do the right things right".

But the system doesn't follow a whole-of-system approach

> *"The urge to save humanity is almost always a false front for the urge to rule."*
>
> – H. L. Mencken

All systems – including rather dysfunctional ones – are surprisingly stable. The current aged and nursing home systems are 'peddling along' based on the disparate 'simple rules' that drive the activities of stakeholders at each system layer. It cannot be stressed enough – all systems always deliver what they are designed for. The current aged and nursing home 'arrangements' are not designed to function as a seamlessly integrated whole. Indeed, there are probably three different systems operating in the aged care domain, each having a different agenda. Or put more bluntly – the current aged and nursing home arrangements are of a design that fail its constituency as it has no universally accepted and 'enforced' focus (purpose). Failing to maintain the system's legislated focus prevents the emergence of system-wide 'simple (or operating)' rules (see Box):

The importance of 'simple (or operating) rules'

To fully understand the dynamics of an organisation as-a-whole one must appreciate the importance of 'simple rules' on the behaviours and ultimately outcomes of an organisation. Simple rules are collectively agreed upon guidelines that inform how all members of the organisation interact within its internal and external environments. An organisation's simple rules should be explicit, and generally number between three and five. Whether by conscious agreement, or by unspoken assent, members of a CAS engage with each other according to such a short list of simple rules. Those simple rules shape the conditions that characterise the dominant patterns (or culture) of an organisational system.

Applying the concepts of 'simple rules' to the current aged care arrangements reveals three different sets – one for the government level, another for the proprietor level and a third for the nursing home (care delivery) level.

The 'simple rules' for the government level:

- Address all identified issues to the maximum extent permitted;
- Responsibility is accepted for actions, where there is a clear direction or a delegation of authority;
- All areas of government are resource-constrained, hence doing more with less is required.

The 'simple rules' for the proprietor level:

- Apply business principles in decision-making;
- Stay within the regulator's rules;
- Avoid overt resident complaints.

The 'simple rules' for the nursing home level:

- Respect residents unfettered autonomy regardless of consequences;
- Always strictly follow the regulator's rules, independent of context;
- Look after yourself[1] – minimise your personal suffering;
- Be creative with using the available limited resources in the care of residents.

The current system design puts residents at risk

The residential aged care system is the responsibility of the Australian Government. Its legislation constitutes the overall framework of the system (*Aged Care Act* [13]) and specifically:

- Defines its purpose and thereby its expected outcomes;
- Provides its financing, and;
- Provides oversight (governance and accountability).

While all aged care is the responsibility of the Federal Government, it does not directly own or operate any residential aged care facilities. The provision of aged care is outsourced to a mix of corporate, not-for-profit organisations, and state and Local Government entities. The aim of aged care services are subjectively defined in terms of wellbeing and independence, i.e. focusing on quality of life [14].

While the stated purpose of the system is unambiguously defined (by legislation), there is no universal shared understanding of the system's purpose among all its agents. This creates inconsistencies and ambiguities that allow different stakeholders to pay more attention to their own interests.

The cascading consequence of ambiguity of purpose

Complex adaptive hierarchically layered organisational systems are governed by top-down information transfer. The Australian Government views those requiring nursing home care as consumers [15] despite the *Aged Care Act* clearly emphasising that the system is for people with needs or recipients of care [13]. This perception neglects the reality that 'people don't choose' to become nursing home residents, nursing home care becomes the last resort to 'keep going'. The 'consumer terminology' subtly prioritises a commercial over a caring culture for the sector. The commercial influence as the basis for system-wide information transfer, while more overt in the for-profit than not-for profit sector, has cascading effects that limits the ability of nursing home staff to deliver the care that the *Aged Care Act* stipulates.

The Australian Government decided not to be 'directly involved in aged and nursing home care' and outsourced the funding and regulation of the aged and nursing home sector to 'so-called independent' government instrumentalities.

Financing

The aged care system can be seen in economic terms only as a series of 'imperfect markets', where little consumer choice prevails and markets are distorted by a concentration at the profitable provider end, with frequent government intervention. The current Australian Government legislation and policy settings are designed to fund the operation of nursing home care based on a disease-specific instrumental indicators of need (ACFI-model [16]), rather than 'overall – physical, emotional, social and cognitive – care needs.' [17].

Oversight – the regulatory frame

Regulation refers to state intervention in economic and social activity, aimed at directing or encouraging behaviour valued by the community, so as to facilitate the pursuit of collectivist goals that might not otherwise be realised and which constitutes a form of 'public law' in the sense that it is generally for the state (or its agents) to enforce the obligations that cannot be overreached by private agreement between the parties concerned [18].

The Aged Care Quality and Safety Commission is charged with the oversight of the aged and nursing home system. However, the regulator is potentially conflicted by its interdependent powers [19]:

- Giving potential operators the right to provide aged care services;
- Enforcing a particular view on how to deliver services; and
- Being the adjudicator of imposing sanction or withdrawing their right to operate.

Besides this the regulator, rather than providing oversight, has adopted an ambiguous compliance framework [19] that infers a prescriptive process-focused micromanagement philosophy. Such an approach stifles any form of flexibility necessary to respond to the often rapid and unpredictable changing care needs of frail nursing home residents. The consequences of this approach are a climate of fear – for proprietors and management, the constant concern about avoiding sanctions and for care staff a 'double fear' of losing one's job for failing to meet documentation requirements and failing to properly care for residents (**Figure 4**).

Proprietors

Proprietors, constrained by limited government funding, are limited in their ability to meet their obligations of providing flexible and adaptive care to meet their residents' needs and to maintain their dignity. Proprietor status – for-profit or not-for-profit – has an impact on staffing arrangements and quality of care outcomes. Financial viability concerns have resulted in 'economy of scale' thinking, with nursing homes becoming bigger [20-22] and more hospital like [22]. Institutionalised nursing home settings are contrary to the objective of providing a home-like environment for a smaller number of (between eight and 12) residents and, contrary to common economic belief, are not more cost-effective. On the contrary, small cluster model experiments have demonstrated their ability to deliver a higher quality of care and higher resident and family satisfaction at a lower cost [23-26].

Workforce

Nursing home care involves three separate, but interrelated, domains:

- Personal care – provided by personal care assistants (PCA) and assistants in nursing (AIN);
- Clinical care – provided by registered nurses (RN – with general, geriatric and mental

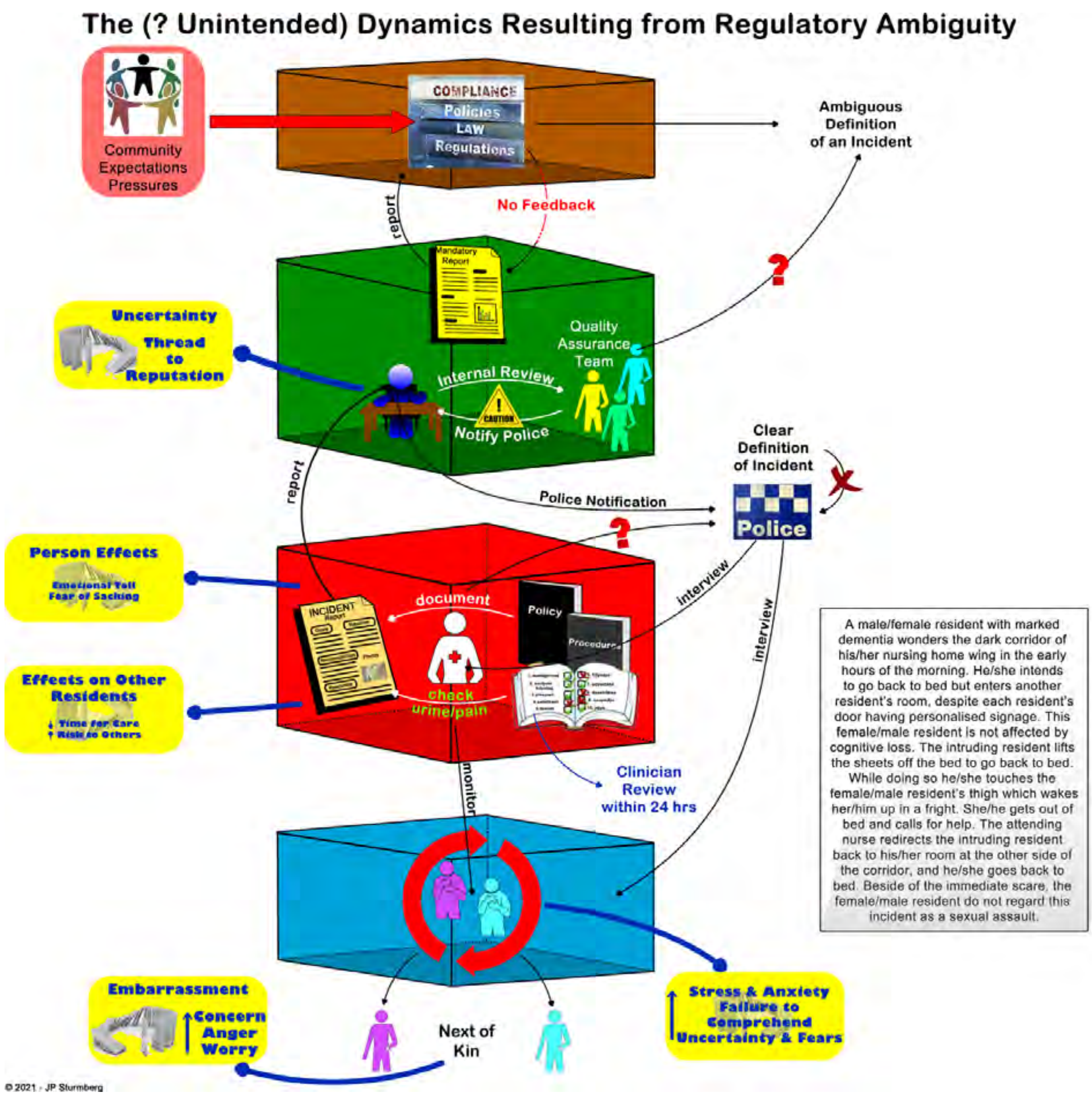

Figure 4 – The intent and the unintended consequences of ambiguous regulations

health experience) and enrolled nurses (EN), nurse practitioners (NP), physiotherapists, podiatrists, dieticians and physicians (primarily GPs and, on a consulting basis, geriatricians and psychiatrists); and

- Social care – provided by lifestyle therapists, diversional therapists and volunteers such as musicians, artists or animal handlers.

However, the *Australian Health Care Act* 1997 [13] only applies a minimalist approach to staffing mix and staffing levels – it requires that providers: maintain an adequate number of appropriately skilled staff to ensure that the care needs of care recipients are met.

These minimalist requirements and the fact that staffing is the highest line item in the budget of a nursing home results in nursing homes employing larger numbers of lowly qualified and lowly paid casual personal care staff in favour of highly qualified – usually permanent – nursing staff [27-31].

Working in geriatric care is widely seen as an undesirable and unrewarding career path. Workloads are high, the job is emotionally challenging and pay is low relative to other settings. This makes it difficult to attract suitably qualified staff with an intrinsic commitment to the care of frail people at the end of their life.

The workplace conditions have two interrelated consequences: firstly, the perception of 'low value' coupled with job-insecurity limits commitment to the workplace and, as a corollary, limits the all-important development of personal relationships with residents. Secondly, staff commitment impacts the quality-of-care residents receive, which in turn increases their risk of otherwise avoidable complications, but also increases the risk of a nursing home being sanctioned.

Residents

People entering nursing home care are getting older and sicker [32] and have increasingly more complex care needs [16] which inevitably necessitates a disease-focused process-oriented approach to resident care. This also endangers a focus on residents' general concerns – the maintenance of personal well-being [33].

A particular concern regarding the safety of the system arises from the weak voice of the resident. They frequently experience the feeling that staff, management and proprietors resent their feedback, or that it gets lost, which prevents the early recognition of emerging risks and allows the embedding of undesirable behaviours and abuse. Resident feedback is crucial for achieving an effective, efficient, safe and seamlessly integrated aged and nursing home system.

And, finally, a widely neglected resident issue is the lack of end-of-life planning and a society-wide avoidance of engagement with death and dying.

Figure 5 summarises the key – overlooked – interdependencies within the current nursing home system.

Section 3: Discussion and transferable learnings

How do we get to where we want to be?

> *"We cannot get to where we dream of being tomorrow unless we change our thinking today."*
>
> – Albert Einstein

As 'all systems always deliver what they are designed for' we need to find a universally accepted focus (purpose) for the nursing home system that achieves the

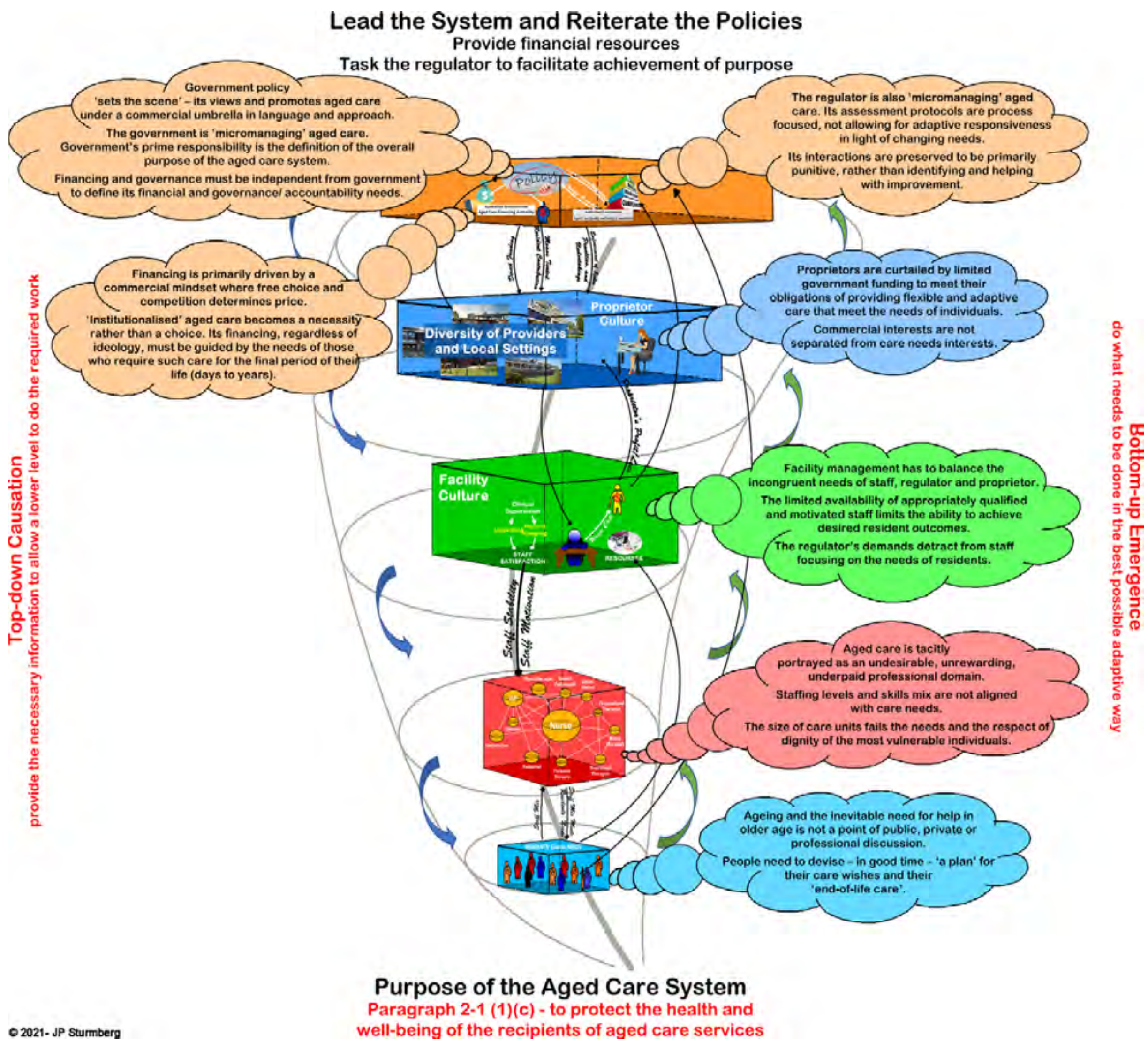

Figure 5 – Summary of the key – but overlooked – interdependencies towards a seamlessly integrated residential aged care system

outcomes we aspire to as citizens and potential nursing home residents. This is only achievable if we – collectively – think differently about nursing homes and the services they ought to provide in terms of meeting the needs and maintaining the dignity of the most vulnerable section of the elderly in our communities. In simple terms, it means unequivocally embracing the purpose of the system, which in turn entails the adoption of new 'simple rules' (see Box):

> ***New 'Simple Rules' must refocus on what matters***
>
> The purpose of the aged care system
>
> The needs and aspirations of each resident
>
> Permission to adapt to rapidly changing resident needs
>
> The resourceful application of limited financial resources
>
> Accountability in the context of the system as a whole

It also entails acknowledging the need for culture change and, consequently, assembling a facilitating leadership team – one that helps 'those who have to do the work to find their locally feasible solutions' [10]. Organisational culture is the focus of individuals' learned behaviours [34]. Thus, testing their understanding of the 'simple rules' is a good first step and might even lead to improvements. Influential leadership guides the application of 'rules-based' behaviours in a mutually satisfying way to achieve the organisation's concerns [35]. It necessitates for some giving up – perceived – privileges, for others to become confident to speak up and being supported in raising issues of concern (**Figure 6**).

A systems-based approach

Four concepts need to be considered in the redesign towards a seamless integrated nursing home system.

- Clearly define the focus (purpose) of the system[2].
- Stakeholder interdependencies must align to achieve the system's purpose.
- The system must entail effective feedback to enable adaptation in a constantly changing environment.
- Ensure the top-down system constraints are 'just right' to allow everyone to do their job.

Applying these four concepts allows for the proper top-down consideration of who – at each level in the system hierarchy – has to create 'what kind of constraints' to achieve the conditions for the seamless integrated function of the nursing home system. At the same time, it allows each level to determine the bottom-up requirements to effectively, efficiently and equitably provide the services that meet residents' needs and maintain their dignity (**Figure 7**).

A new set of simple rules

'Simple rules' or 'how to rules' are the – tacit or outspoken – operating principles that determine the dynamics and the achievements of a system. They provide the necessary 'guidance' for decision-making to all agents, regardless of their place and role in the system.

Developing a new set of 'simple rules' is a deliberative process – it must take into account the system's values and its purpose. Aged and nursing home care is about providing frail people with the necessary support that meets their needs and maintains their dignity. Suggested 'simple rules' to achieve an effective, efficient, equitable and sustainable aged and nursing home system are:

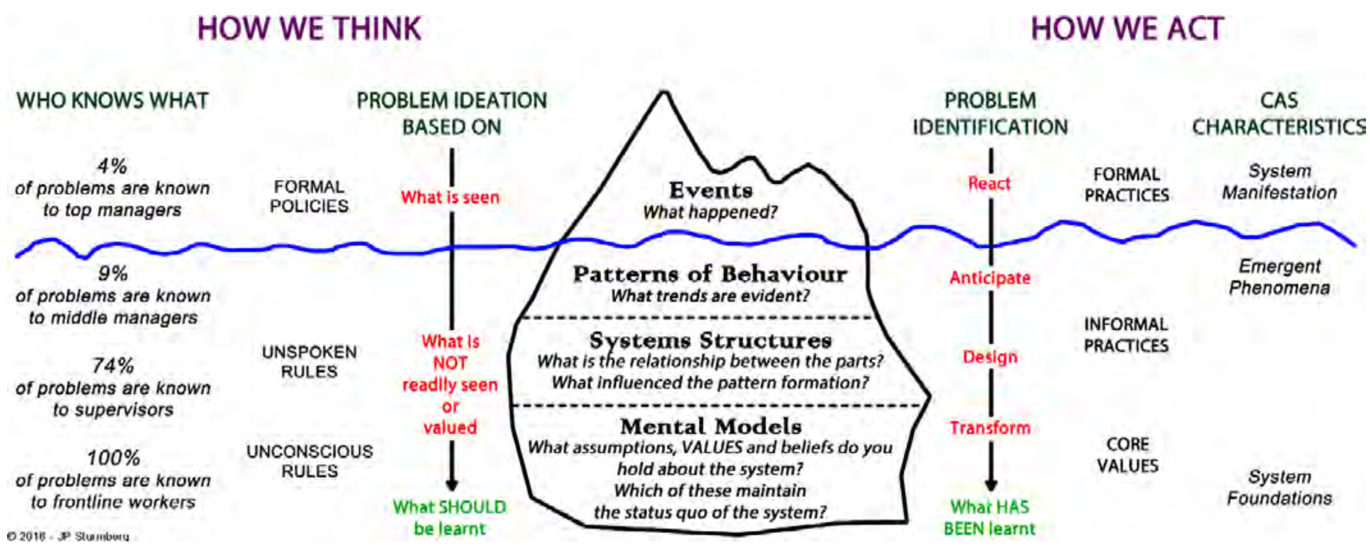

Figure 6 – The 'iceberg metaphor' of understanding an organisation and the impact on its function. Note: Top level managers don't know the majority of problems encountered by the members of the organisation. Their responses typically are reactive rather than explorative (reproduced from [9]).

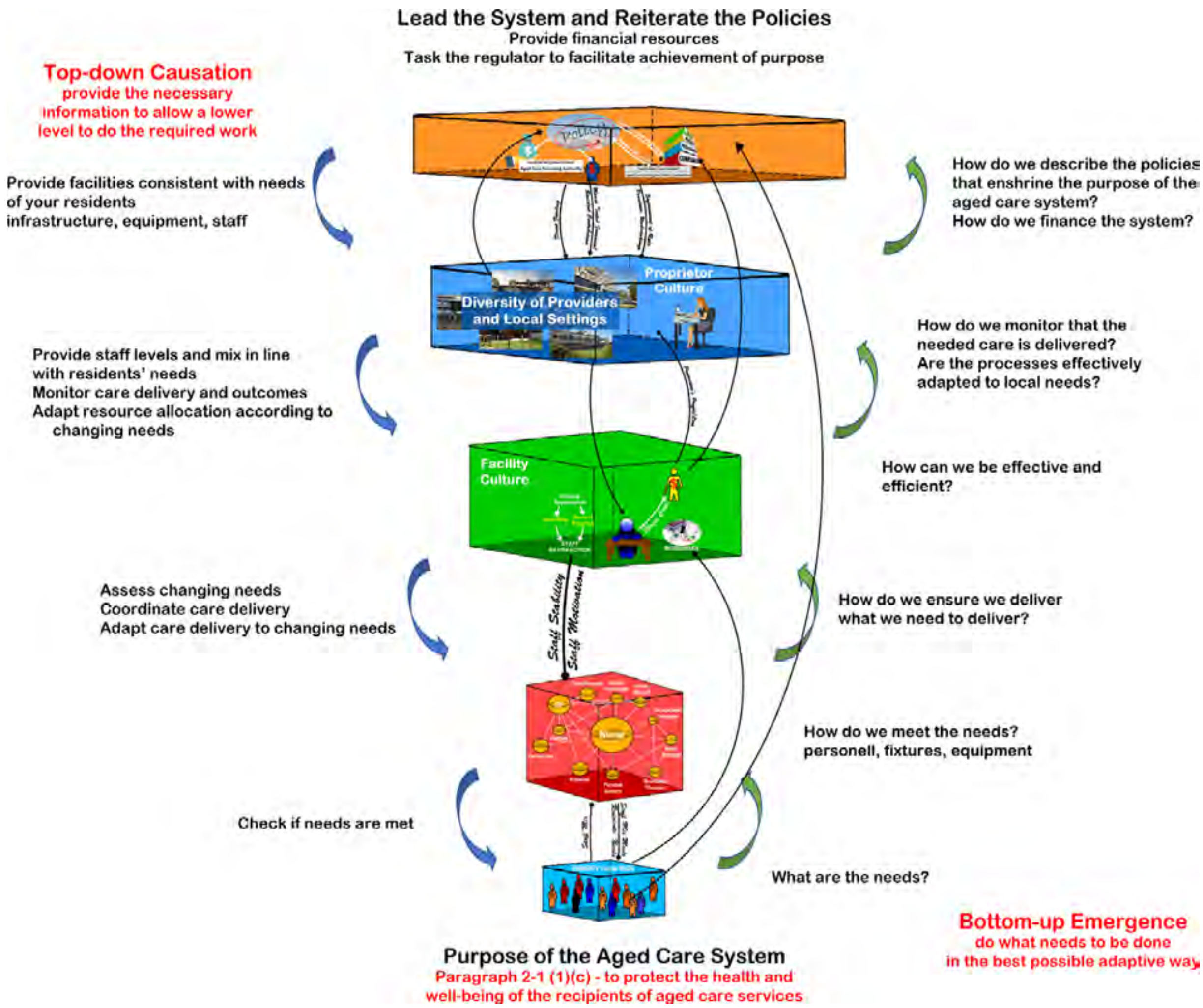

Figure 7 – Creating a seamlessly integrated complex adaptive aged and nursing home system

Suggested 'simple rules' for a redesigned system

First and foremost, focus on the purpose of the system – to provide care that achieves residents' desired quality of life and maintains their dignity

Adapt your behaviours and actions to emerging challenges – within your level of expertise and responsibilities

Share your concerns

Engage in the problem-solving processes

What does this mean in practice?

The most effective and efficient way to get to where we want to be is through a collaborative redesign process [36, 37]. Redesigning is as much a philosophical approach re-examining the purpose and the value of the system, as it is a pragmatic technical exercise in brainstorming and testing new approaches.

A blueprint for the redesign of the aged and nursing home system might entail the following – interconnected and interdependent – steps and considerations (**Figure 7**). This blueprint takes account of the key systemic features of complex adaptive organisations:

- The need to know the purpose of the organisation;
- An appreciation of the hierarchically layered network structure of an organisation; and
- The top-down impact of constraints on limiting the emergent bottom-up abilities to do the work that needs to be done.

The success of an organisation relies on understanding and harnessing the feedback loops that exist within and across the networked layers of the organisation. Organisational leadership is dispersed across the organisation and leaders distinguish between the – *top-down* – focus on determining WHAT needs to be done. Leadership trusts their staffs' aptitudes and sense of responsibility and explicitly grants – *bottom-up* – permission to conceive (and adapt) HOW that work will be done [10].

Special considerations

Getting to a seamlessly integrated complex adaptive aged and nursing home system is principally a matter of unifying all stakeholders behind a common purpose, goals, values and 'simple rules' agreement. Nevertheless, a number of issues need to be considered in greater detail.

How to assure one stays on track – the need for an 'outcomes' framework

The first issue to address in the redesign of the aged and nursing home system is a change in its oversight framework. What the legislation proclaims, and what nursing home residents aspire to from their care, is quality of life and the maintenance of their dignity. Oversight needs to focus on what matters, it must be outcomes, not solely process/output, focused. It is the outcome to be achieved that determines the services required, which in turn determines the resources needed and the skills mix of staff to deliver the required care. Delivering the required care must be effective, equitable and efficient (addressing primarily policy concerns) which closes the perpetual loop that ensures ongoing high-quality care (**Figure 8**).

How to finance an outsourced 'common good' like aged care – for-profit or not-for-profit service provision

Society throughout history has contemplated the nature and the purpose of 'common good' provisions. Adam Smith argued that in order to realise common interests, society should shoulder common responsibilities to ensure that the welfare of the most vulnerable is maintained [38] and John Rawls pointed out that the common good is the core of a healthy political system – common goods are provided equitably to everyone's advantage [39].

The promotion of neo-liberal doctrines, starting in the 1970s, have blurred the otherwise longstanding notion that healthcare, and by implication healthcare towards the end of life, is provided for the benefit of society at large. The idea that healthcare can be broken down into distinctive bits that have a 'distinctive value and thus can be sold at a price' has led to an 'industrious understanding' of healthcare as the 'delivery of a series of defined products'. This view negates the fact that the effects of healthcare as-a-whole arise from the interdependent impacts of 'global care' and the 'instrumental care' of specific conditions.

These shifting appreciations allowed the emergence of for-profit and not-for-profit providers in health and aged care. However, the status of a provider organisation necessitates different objectives. While both want to be efficient in the way they provide care, corporations – by law – have a primary duty to shareholders to

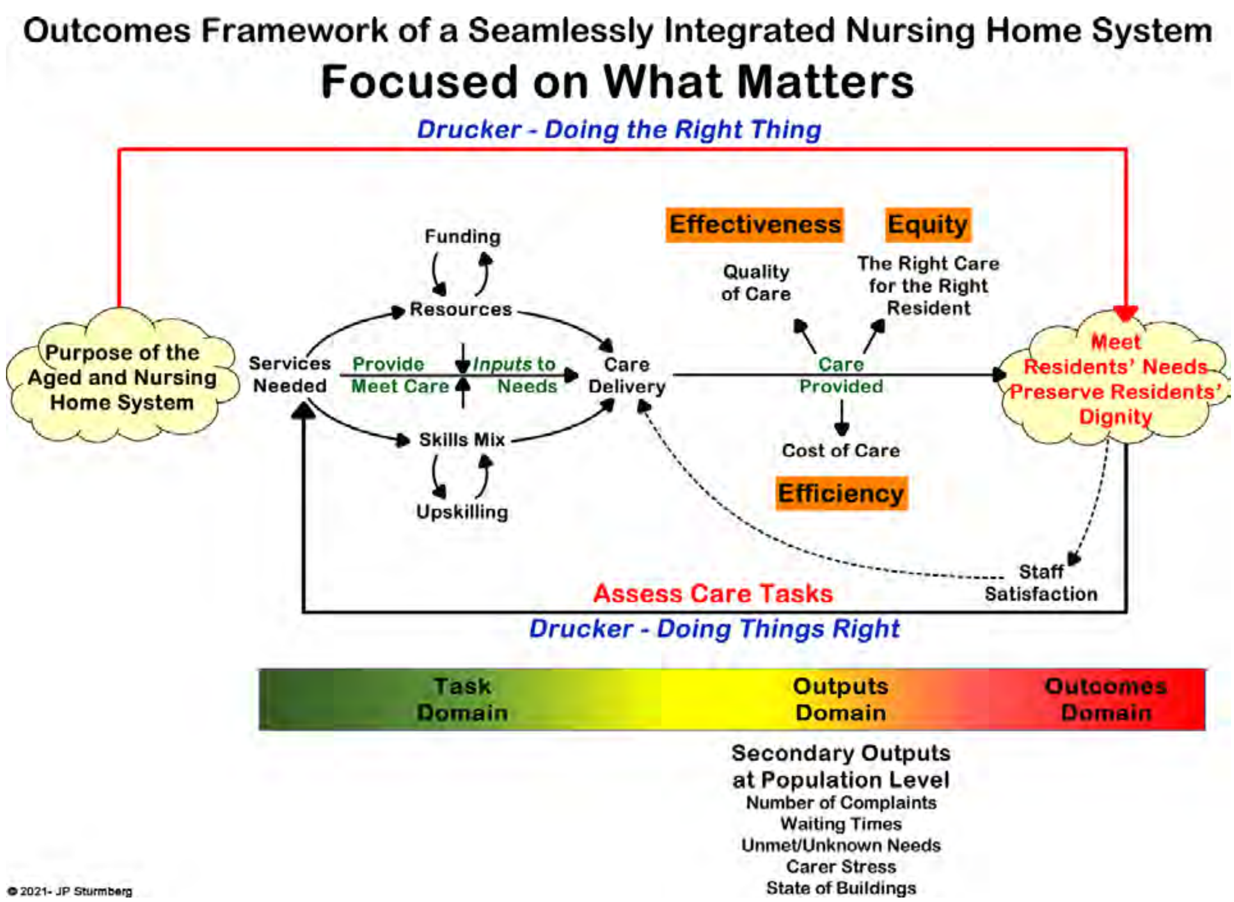

Figure 8 – Dynamic outcomes framework for an outcomes-focused adaptive aged and nursing home system

work towards profit maximisation, whereas not-for-profit entities are free to focus on the most effective way to apply their resources to deliver care outcomes for stakeholders.

How to resolve the governance and accountability tensions – the need to refocus on 'what matters'

The focus of governance and accountability frameworks needs to resolve the tensions arising from its build-in current ambiguities – a new framework must clearly state what matters, how to assess what matters and by what means it can be achieved. Only then can the prevailing culture of fear and the inherent confusion among staff be resolved, allowing them to most effectively, efficiently and equitably spend their limited time managing the often rapidly changing needs of residents under their care (**Figure 9**).

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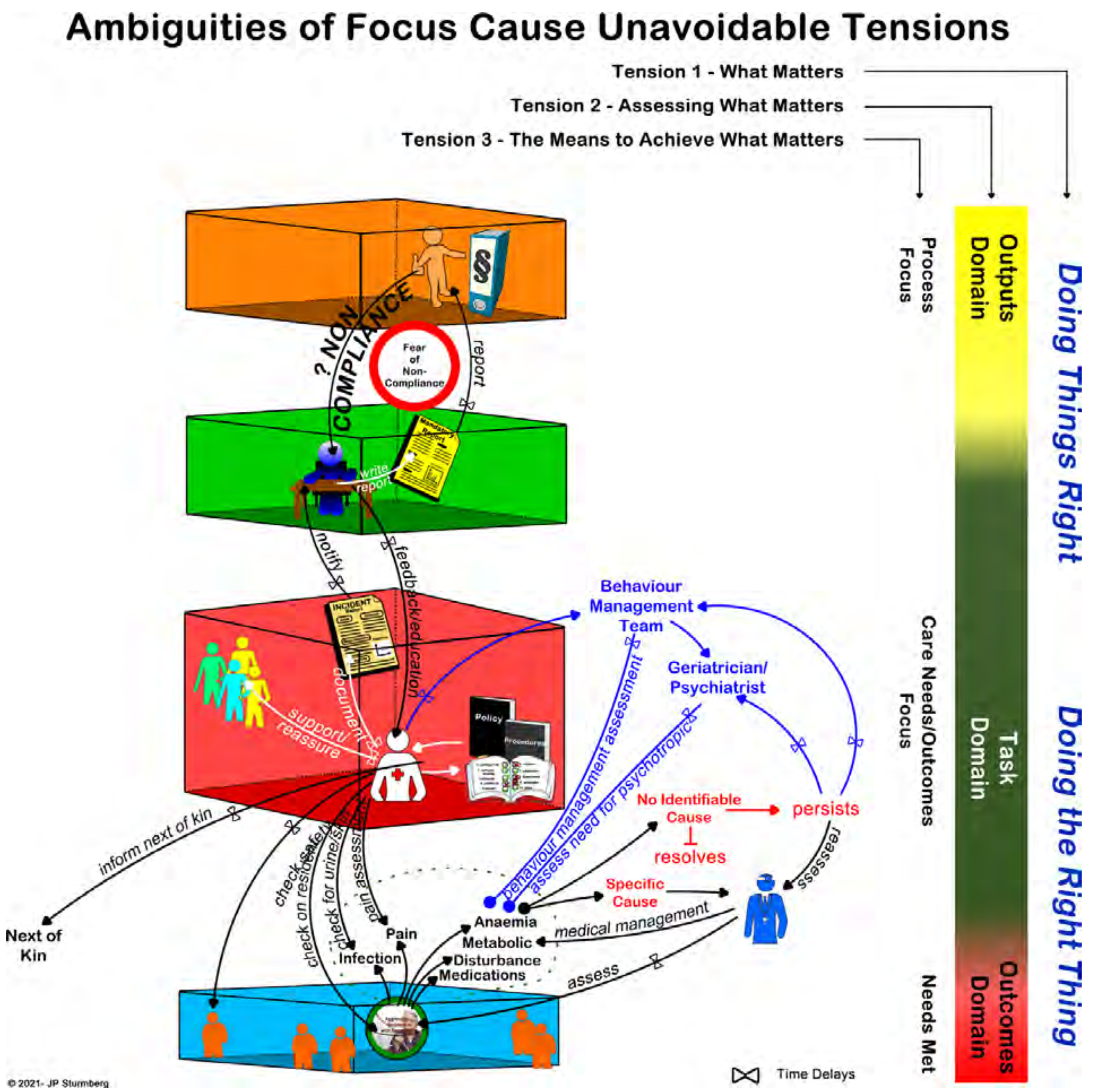

Figure 9 – Responding to a 'critical resident incidence'. This system and influence diagram clearly illustrates the central role of the nurse in managing a critical resident incident and its multiple, and multi-layered consequences, as much as the impacts and roles of external agents. Care staff in the first instance is outcomes driven, where the desired outcomes define the necessary tasks to be attended to. The failure to recognise that outcomes should determine output and process measures creates tensions resulting in uncertainties and fears – both of which hinder system improvement

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Endnotes

1. Resulting from: (1) Employer sponsored visa holders (a substantial proportion of nursing staff) are bonded to do their time in residential aged care; any misadventures can lead to deportation (enforces a mental mindset of: do your prison time and move on); (2) the 'more direct' power dynamics between employers and employees in nursing home settings compared to hospital settings
2. This is already defined by the *Aged Care Act* 1997
3. That which is seen as best for a whole community and not simply for any individual or small group within that community. This may be seen in purely utilitarian ways, but it may be founded upon natural law theory. The ideas behind law and democracy assume that the common good is something that can be achieved, or at least should be pursued. (The Free Dictionary – https://financial-dictionary.thefreedictionary.com/Common+Good+(organization)
4. Common good, that which benefits society as a whole, in contrast to the private good of individuals and sections of society. (Britannica – https://www.britannica.com/topic/common-good)

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Humanitarian supply chains during COVID-19: systems failures, recovery and emerging alternatives

By Claire Travers, Anna Lowe

Executive summary: The disruption caused by the COVID-19 pandemic has been acutely felt in the humanitarian aid sector. Through a series of qualitative interviews, this case study investigates systemic failures in humanitarian supply chains including a) unavailability of items, b) price volatility, c) delays in delivery and d) quality assurance issues. The results offer humanitarian organisations, donors, and academic researchers next steps in improving humanitarian supply chains and future avenues of research.

Tags: humanitarian logistics, emergency logistics, COVID-19, supply chain management, disaster logistics, qualitative, atlas TI, humanitarian supply chains, humanitarian aid, globalised networks

Section 1: Background and introduction

At the time COVID-19 was conferred with pandemic-status[1], 57 pre-existing humanitarian crises were receiving aid provision, affecting 118million people and with an estimated funding requirement of approx. $30B (UNOCHA, 2019). Early estimates indicated an additional $2.01B and 1.3B units of personal protective equipment (PPE) for personnel was required to continue the provision of humanitarian aid, and to accommodate for new or amended programmes to address COVID-19. Getting these items would prove to be impossible in the immediate wake of COVID-19 due to social measures required to mitigate the spread. On 13th February, the Chinese Government issued an extension of order to shut down all non-essential companies, including manufacturing plants, in Hubei Province which remained in effect until 8th April impacting manufacturing and exportation of key goods. Globally, 100% of national governments responded to the pandemic with social measures aimed at mitigating the spread of COVID-19, such as restricting movement of citizens, suspending the conducting of business, and closing borders, ports and points of entry, impacting supply chains essential for humanitarian response. When land, air and sea points of entry (POE) begun operating, it was with reduced capacity of up to 66%. The provision of aircraft belly capacity usually made available for humanitarian goods due to decreased to 89%. These supply chains disruptions heavily impacted the provision of humanitarian aid, with 80% of programmes reported refocusing activities (ACAPS, 2020), and interview analysis indicating a slowing or suspension of non-COVID-19 activities. The coverage of need by the end of the case study period (Oct 2020) had decrease to 28%, and the humanitarian funding requirement had increased by $10.59B[2].

A model for complex system failure produced by Engineering X and York University, depicted in **Figure 1**, categorises systems failure as a product of exacerbating factor on a complex system, compounded by a failure of design-time and operation-time controls. This case study uses the framework in a qualitative analysis of 17 semistructured interviews with humanitarian personnel to characterise the experience of supply chain failure between February to October 2020.

This case study positions itself as a source of reflection for the humanitarian sector on the experience of global pandemics; and identifies ways to amend the systemic controls to better respond to future pandemics.

Section 2: Analysis and insights

What was the systemic failure?

During the analysis of the interviews, supply chain disruptions were characterised under the York Framework as a 'systems failure' and was described in the following four ways.

Price instability

Prices of PPE, non-COVID items and transportation fluctuated throughout the case study period and affected all geographic reasons. To an extent price instability was due to an initial surge in demand for both products and transportation handling outstripping capacity. 70.5% of interviewed participants reported experiences with both

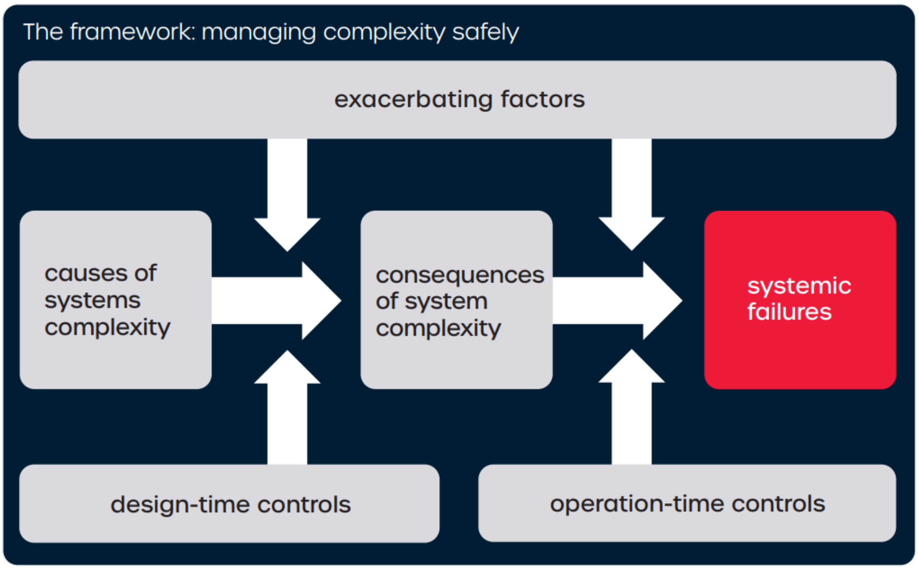

Figure 1: The York Framework

unpredictable pricing. Interviewees commonly reported prices changing at a rate that made it hard or impossible to budget, procure and deliver items. At a local level – national and regional – the price instability was more pronounced then reported from HQ participants. Experiences of price volatility were exacerbated by the slow administrative processes of consolidation and purchasing. When budgeting and assessing needs for PPE, practitioners found the price would change between finalising the purchase order for items and services, approval and submitting the order to vendor and supplier. Even when items or transport were made available free of charge through in-kind offers with the private sector, the lengthy procedures did not allow these benefits to trickle down to speedy supply and delivery of items.

Items unavailable

70.5% of interviewees mentioned scarcity or an inability to source, purchase or receive items. In local/national markets the scramble for items meant that individuals did not have the necessary items to safely continue to deliver aid. Some participants reported that this was a reason for halting programmes that required close interpersonal contact, including the medical and sanitation interventions, as well as protection activities such as conducting child-friendly spaces or gender-based violence activities. Other participants mentioned there were experiences of theft from their PPE inventory during times when items were not available in markets. At a global level, manufacturing delays and a surge in demand for PPE, prompted suppliers to issue minimum order quantities (MOQ). Interviewees commonly reported the pooling of demands and purchase orders in order to qualify for these suppliers.

Delivery delays

Where items could be procured, there were commonly delays in the delivery of those items. 64.7% of interviewees reported lead times increased, on average by 3 months. Interviewees ascribed delays in delivery to a lack of capacity for transport. With decreased commercial flights, the demand for cargo flights pushed prices up. In addition, interviewees mentioned bottlenecks at POE including government-mandated closures, staff shortages due to social distancing and illness/death, or changes in importation requirements. Where organisations used WFP-operated flights, these delays were less acutely felt. Some participants notes that delivery delays prompted diversifying suppliers, including local suppliers.

Quality concerns of items

70.5% of interviewees experienced quality concerns when the items were delivered, specifically in new products (such as PPE). These concerns were reported in both the items procured locally or globally, but more frequently from deliveries from new suppliers. Participants reported PPE not fit-forpurpose as it did not include a complete set of items (e.g. Masks without strings to attach them). A minority of interviewees spoke of their experience of "false promises" – where a sample batch was of sufficient quality but on delivery, the full order was not of comparable quality. On the occasion that sub-quality goods were delivered practitioners did not use them for activities involving affected populations including in programme activities.

How did this situation come about?

Supply chain disruption during February to October was not unique to the humanitarian sector. Humanitarian supply chains, however, faced specific barriers in procuring, transporting, and delivering these items to frontline personnel and affected populations.

System inflexibility

Humanitarian supplies are procured in humanitarian response using funds provided by donor states. Ordinarily thresholds are used to control how this process is conducted, with purchase orders over a threshold requiring public tendering, and the evaluated of at least three bids by an independent panel with the organisation to ensure quality, fair price, and to off-set the risk of corruption or conflicts of interest. The use of stockpiled supplies is also common in a humanitarian crisis, with regional stockpiles for long-life items (such as tarps, soaps, sanitary items). Pre-approved suppliers are also typically preferred, but these suppliers can only supply already known inventory and cannot pivot for new items. The process of vetting, approving, and listing suppliers is a lengthy and administratively difficult process, typically meaning that new suppliers cannot access these systems.

Although the humanitarian sector has enjoyed a move to standardise programmes, the specifications for items vary between organisation and tend to be slightly different from those found in commercial markets. For example, tarps used in humanitarian response required in shelter response have subtly different requirements then commercial tarps; and non-food item kits vary in small ways between organisations. This has essentially led to siloed parts of the supply chain – including manufacturing and supplying these key goods.

During COVID-19 common standards for items specs were issued in May 2021. However, organisations and programmes that would not usually handle PPE items did not have suitable preapproved standards, item specifications or suppliers to make rapid purchase orders. Inventory codes, supplier approvals and market assessment (where done) were done rapidly, drawing on technical personnel which the sector has easy access to. Many interview participants felt that their organisation was well-equipped to rapidly understand and respond in these ways, given their prior experience in health emergency and epidemic responses. In the initial lag in supplies, regional stockpiles of PPE and other humanitarian items ran out and local markets were subject to spikes and dips in pricing of essential items including PPE.

The majority of those interviewed reported that they had to rapidly diversify suppliers to get the stocks required, and this is when reports of "false promises" or poor-quality items were introduced. The skills and resources for rapidly diversifying, localising or introducing new suppliers simply does not exist within a system that has been built inflexibly and with a reliance on a few, with inflexible elements

Reliance on global supply chains

Global transport of humanitarian goods relies in part on the same supply routes as commercial shipping. During a humanitarian response, national governments may apply their own importation restrictions to prioritise supplies for humanitarian response, or export bans/restrictions on items they require. During COVID-19, shutdowns of ports, air borders and points of entry (POE) was swift and establishing alternative routes was time consuming. In some cases, the interviewees noted that they set up their own supply chains, but without the necessary organisational knowledge or resourcing. Even when reopened, many POE were operating at a reduced capacity due to new health and safety measures (social distancing and quarantining goods) as well as staff shortages and illness. Delays are witnessed particularly at border crossings throughout East Africa (east at the Kenya/Uganda Malaba border, Uganda/South Sudan border) and West Africa (Central African Republic/Cameroon border).

Lack of local market awareness

The knowledge of market assessment, process and compliance information was markedly different between national and HQ level. This was particularly difficult during COVID-19 as many expatriate staff were given the option to repatriate, taking organisational knowledge with them and brain draining national offices. Although the desk review found good guidance has been issued since 2020, it also found a lack of market assessment methodology that was clear and tested for non-food items. At national level, the lack of market awareness hampered the ability of country programmes to quickly diversify supply chains or set up new suppliers, quality test items, and complete required compliance and custom paperwork. National-level interviewees noted the systemic separation between procurement and programmes staff and "siloing" of HQ and national knowledge, which contributes to this knowledge gap.

Information sharing about suppliers, vendors and manufacturers was done by national staff through informal channels, including WhatsApp, Facebook, and door-to-door networking. Some participants reported that this work was not compliant with donor requirements, leaving lingering concerns over their performance in an audit. On some occasion, a backdating of documents was confirmed as a common practice for mitigating this risk.

A lack of pandemic planning

While epidemic response at a regional level is commonplace in humanitarian sector, participants reported their organisation had previously prepared a pandemic. Whilst some respondents had emergency procurement and logistics procedures on hand, others did not. Interviewees from HQ and Regional level seemed to be more familiar with the procedures, indicating that where there was effort for contingency planning, the findings and lessons were not communicated to national offices. Those interviews which mentioned the use of emergency procedures and business continuity documentation, noted they were out-of-date and/or hard to find.

This was compounded by the lack of general funding available for updating, maintaining and modernising logistics procedures. Ordinarily only 7-15% of budgets for humanitarian response can be allocated to the core costs, which includes not just logistics, but communications, fixed costs etc. As such, very few participants felt their systems and procedures were equipped to handle the pandemic, even if the procedures were available. In organisations where injections of funds had recently been made to update systems, technology or personnel, the experience of the systems failure was markedly different. Interviews with individuals from those organisations more frequently mentioned positive experiences during this time – feeling supported, confident in the decisions being made. Reactive funding also complicated the ability to procure items quickly. In interviews were crisis modifiers were mentioned, respondents felt this enabled them to more quickly procure emergency stock, allowing them to continue humanitarian response activities.

Section 3: Discussion and transferable learnings

How can the system cope? Dynamic re-design from COVID-19

Funding mechanisms redesigned

This included WHO through the Immediate Response Account (IRA), which was complemented by The Global Fund (who reprogrammed funding to release early finance streams), the Gates Foundation (who provided bridge-funding to enable rapid deployment of supplies), and The Solidarity Fund (which launched in March). On the 6th April UNOCHA issued guidance on the CBPF which allowed for critical injections of finance into existing programmes. Importantly, temporary or time-limited flexibility protocols such as remote audit and financial monitoring, issuing a blanket no-cost extension (NCE) to existing programmes, authorising the use of e-signature on documentation, issuing a 15% then 20% budget line flexibility, and removing the traditional caveat for 'triggers' for funds. This effectively freed up funds usually allocated to one type of emergency for use in COVID-19 response, including to logistics and supply chain management costs. Although logistics and supply chain management are not specifically mentioned, the above serve to allow for flexible financing of costs ascribed to these areas of operations.

Organisational and donor commitment to streamlining purchasing

Nearly all respondents confirmed that during the time period in question they experienced the benefits of a change in standard operating procedures or invoking emergency procedures. These essentially temporarily lifted the thresholds required to undergo a lengthy bidding process. In addition, where crisis modifiers were available respondents felt able to more quickly secure items already in the supply chain and build out stockpiles. Including crisis modifiers in all humanitarian and resilience building activities in the future would be a clear and simple way for donors to enable rapid pivoting of activities and activation of local supply chains in future pandemics, global port closures, or bottlenecks in shipping lanes (e.g Panama).

Virtual supply chain coordination

Early April the SCTF convened the Covid-19 Supply Chain System (CSCS). This system was designed with three components; 1) a control tower is erected in Geneva, dedicated to consolidating demands, allocating inventory and administrating the delivery of products, 2) three purchasing consortia for biomedical, PPE and diagnostic products respectively, and 3) a suite of planning tools which is launched on the WHO Partners Platform. Designed to provide real-time tracking of goods to support the planning, implementation and resourcing of nation states; to help governments access the Essential Supplies Forecast (ESFT); and the Supply Portal to consolidate demand per National Action Plans alongside the Emergency Service Marketplace (ESM). Delivery Hubs were erected in eight countries: Global Hubs in Guangzhou (China), Dubai (United Arab Emirates), and Liege (Belgium). Regional Hubs in Kuala Lumpur (Malaysia), Addis Ababa (Ethiopia), Panama City (Panama), Accra (Ghana) and Johannesburg (South Africa). The CSCS accounted for approximately 50% of the essential supplies secured by partners in 2020. The report suggests that including national and regional purchasers could increase access and ownership of a centralised supply chain system, and that a country-facing platform would be beneficial to connect to partner platforms and engage national government and regional institutions. (The Yellow House & WFP, 2021

Local market initiatives for local production

Participants reported that looking for humanitarian supplies in new vendors, suppliers or local markets. In some interviews the use of non-traditional suppliers was mentioned – specifically the collaboration with existing programme beneficiaries or local manufacturing groups to make PPE. On 12th May the Tech Access Partnership was launched by the United Nations Technology Bank, together with the UNDP, UN Conference on Trade and Development (UNCTAD) and the WHO. The Tech Access Partnership was created to address critical shortages of essential health technologies and equipment by connecting manufacturers with critical expertise and emerging manufacturers in developing countries, to share the information, technical advice and resources necessary to scale up production of essential items. This represents the explicit inclusion of local production capacity to meet shortages and delays in key items, however the initiative is not heavily resourced and does not appear in the Supply Chain Task Force or the WHO COVID-19 Strategic Preparedness and Response plan (SPRP). Future pandemics would benefit from a diversified and localised supply chain, to help cope for breaks in global supply.

Cash and Voucher Assistance (CVA)

The G-HRP July update noted the use of multi-purpose cash assistance to support local markets being used by multiple humanitarian actors. (UNOCHA, 2020). This is supported in our primary data collection as well, with participants noting the rapid scale up on CVA in three key ways – the increase in number of registered recipients of an existing programmes, removing the conditional or work requirements for the cash programming, or setting up new cash programmes to complement or replace NFI and food programmes. In the interviews this was a modality that allowed humanitarian activities to continue quicker than waiting for items would have. This was reported across sectors – in protection, medical or health programmes, food security activities and in sanitation projects.

Standardising of item specifications

13th March, the European Commission Recommendation (EU 2020/403) on conformity assessment and market surveillance procedures within the context of the COVID-19 threat, included the requirements for the design, manufacturing and placing on the market of Personal Protective Equipment (PPE) for COVID-19. This made procurement of items easier as clear standards were the same across organisations and donor bodies. Doing so for other items, or offering a reflexive specification dependent on local markets and available manufacturers, could prove very valuable for future response. Some interviews mentioned that during this time items were available that would not have been ordinarily – including items made by affected populations who were temporarily inducted into the supply chain. Once the temporary measures were lifted, however, these items could not be procured any longer.

Investment in supply chain visibility

For rapid response personnel and infrastructure must be updated to allow organisations to better oversight of inventory and to conduct, access and understand market assessments efficiently. Interviewees from organisations in which investment in technology and logistics infrastructure had been made recently were better positioned for response to system failures. Personnel with appropriate qualifications within the organisational structure were key, and technological enablers including digital inventory tracking and e-compliance products were mentioned as key to safe, swift and ongoing operations.

Appendix 1: Methodology

In this section, the search methodology for desk review and data collection is explained. Data collection was conducted for this case study, through 20 semistructured interviews of humanitarian programme and logistics staff from UN agencies, the IFRC, INGOs, and CSOs. The interviews were transcribed and anonymised and then analysed using the York Framework. As such this section also describes the York Framework and discusses the amendments made to it for the purposes of this analysis.

Desk review

The desk review included both peer-reviewed and grey literature relevant to the topic. This was used to describe the system complexity discussed below (section 3), and to construct the timeline above (section 1). The desk review was also used to inform the semi-structured interview guide which was used throughout the data collection stage.

In order to identify the peer-reviewed literature relevant to the topic, a set of keywords used for an initial search was developed. Searching for papers was done through a combination of keywords: where at least one from set 1 and one from set 2 was present. This search sourced papers from Google Scholar, Scopus, and the IEEE Xplore Library for Global Humanitarian Technology Conference. A search for peer-reviewed literature produced XX papers. Specifically, the keywords in Set 1 were used to locate studies in the humanitarian logistics, or disaster management field, and those in Set 2 were used to identify subject specific papers.

Keywords (Set 1)	Keywords (Set 2)
humanitarian supply chain humanitarian logistics	COVID-19 covid19 nov-cov19

Grey literature was collected from primary sources including: UNOCHA, Relief Web, IASC, UNDOS, WHO, WFP, and INGO policy statements and reports. To be relevant to this study the grey literature was also exposed to the same inclusion criteria: it had to be published during or about this time period. and include a mention of "supply chains" and/or "logistics".

Semi-structured interview development

Within the remit of this case study was to develop new data via a series of semistructured interviews (SSI) with humanitarian sector professionals. Conducting SSIs supports an exploratory approach (Van Korgh et al., 2012), in that it gives the opportunity to collect a rich quality of data. The objective of these interviews was to capture experiences of aid sector professionals during the period from February to October 2020.

As such the unit of analysis was the community of humanitarian practitioners, which were clustered into programmes and logistics staff[3].

Within the humanitarian sector the former and the latter areas of operations usually operate with different personnel, budget streams, and networks or clusters of coordination. In order to make an interview structure that would work for both types of personnel, an interview guide was developed with a total of 6 question set (see Annex Xi for question set, justification and coding).

This semi-structured interview guide was developed and piloted with three interviewees from different organisational samples. In doing so, another unit of analysis was identified: Organisations, which were clustered into: UN Agencies and IFRC; International NGOs, and National NGO or CSOs4[4].

Interviewee selection and interviews

The interviewees were mostly selected through professional networks. A call for participation was developed over and shared on LinkedIn humanitarian logistics groups, on the lead authors personal site, and distributed through email lists for the Local Procurement Learning Partnership (LPLP) and the Humanitarian Logistics Association (HLA). Candidates were also found over LinkedIn, and pre-screened for employment over the research period (non-continuous was allowable), within an identified organisation type. Finally, interviewees were asked to suggest others suitable for participation in further interviews (snowball sampling) (Huberman & Matthew, 1994).

The lead author participated in 100% of the interviews, for the purpose of replication logic, and a sample of the interviews were observed either live or after the fact by a second author, to reduce the possibility of interviewer bias (Yin, 2003). Demographic data was collected during each interview (See Appendix 2 for demographic details). The interviews lasted between 70 and 90 mins, with a mean of 83 minutes.

Transcription

Approximately 25.5 hours of recorded material was collected and transcribed. The HIAT method was utilised (Ehlich, 1992). The transcription was done by a research assistant who was not present for the interviews. During this process the data was stored as coded word files, and the names, organisational name, and identifying information was redacted.

SSI analysis

Atlas TI was used to analyse the transcribed interviews. A total of 17 interviews were included in this case study. A mixture of inductive and deductive coding was used for this study (Fereday & Muir-Cochrane, 2006). Using these strategies iteratively allowed for flexibility in coding, and led to the development of theoretical categories in line with what we can source in the data.

A deductive code manual for this study was developed, serving as a data management tool for organizing segments of similar or related text to assist in interpretation (Crabtree & Miller, 1999). The code manual was tested against a sample of three interview transcripts (each from different organisations), and these were coded by authors, independently. Following the coding process of the transcripts using the predefined codes, the results were compared, and a few modifications to the predetermined code template were required.

Inductive analysis was also conducted by both authors of an additional three interviews, using in-vivo coding for line-by-line descriptive codes (Charmaz, 2006). The descriptive code fragments were discussed considering the existing code manual and where required, modifications to code levels and concepts where made (see Limitations and Scope below). The remainder of the interviews were analysed in line with the revised code manual.

Limitations and scope

This case study is limited by timeframe: February 2020 to October 2020. This window represents the acute onset of COVID-19 and the period of time when the supply chains were most critically affected. After 3rd February there was policy on COVID-19 provided by the United Nations, and as such we would expect this to be a period of time within which humanitarian practitioners become aware of and able to prepare for and respond to COVID-19. Before this date, whilst there may well have been awareness, there was no remit or expectation on sector professionals to be briefed. This case study is interested exclusively in the activities, experiences, and awareness of individual practitioners. By capturing these experiences, the case study aims to catalogue and codify supply chain failures and coping mechanisms within this time period.

Appendix 2: SSI structure and code manual

Below is the semi-structured interview guide developed for this case study, including code tree devised with a deductive method.

Set	Questions	Code
1	Tell me about when you first remember learning about COVID19?	Source of first information Month of first information Reaction to first information Month of organisational communication Organisation preparedness plan
2	How did your organisation prepare for COVID19? What operational guidance?	Causes of Organisational changes – Donor changes – Finance Unavailable – Government Restrictions Examples of Organisational – Deployment changes – HR changes – HQ Policies – Meta policies Positive Organisational coping mechanisms Negative organisational changes
3	What were some significant changes you noticed on your programmes during Feb-Oct 2020? Why did these changes happen?	Changes to programmes – Programmes Halting – Programmes Slowing – Programmes Altered Causes of changes to programmes – Changing Need – Changes in Staffing – Donor changes – Finance unavailable – Supply chain disruption – Government Restrictions Impact of changes in programmes – Beneficiary: Lose of life – Beneficiary: Lose of services – Delays to services/distribution Sectors of Programmes Effected
4	What were some significant changes in your supply chains during Feb-Oct 2020?	Supply Chains System Failure – Items not available – Delays in delivery – Price Instability – Quality concerns of items Causes of Supply Chains disruptions – External to the system (exacerbates factors) – Internal to the System (design time/operation time controls) – Redesign Controls – Latent Controls Key Goods
5	During the period of Feb-Oct 2020, what would you say were the critical moments/ strain points for you?	Cause of Strain – External to the system – Internal to the system Impact of strain Month of strain
6	Was there anything that you wanted to do but couldn't – and why not? OR What would you do differently if you could?	– Prepositioning of goods – Enhanced SCM – Improved Market Awareness – Better coordination – Improved operational guidance

Appendix 3: Demographic data

I-CODE	Which best describes your gender?	Which best describes the organisation you were with during Feb-Oct 2020?	Which best describes your employment in the organisation you were with during Feb-Oct 2020?	Which best describes the level you were stationed at during Feb-Oct 2020?	Where were you deployed/stationed/ based during Feb-Oct 2020?
01-1505	M	UN Agency	Coordinator in logistics	National	SYR
02-2305	F	UN Agency or IFRC	Mid-management or coordinator in programmes	National	LLW – MAL
03-2505	M	National NGO	Mid-management or coordinator in programmes	National	CAL/KEOS
04-0306	M	INGO	Senior management in logistics	HQ	AMA
05-1606	M	Private partner	Senior management in logistics		LDN
06-0507	F	Private partner	Senior management in logistics	HQ	LDN
07-0907	M	INGO	Senior management in logistics	HQ/Regional	AMN
08-1207	F	CSO/National NGO	Senior management in logistics	Regional/ National	Fiji
09-2107	F	INGO	Mid-management or coordinator in programmes	HQ	Geneva
10-0908	F	IFRC	Coordinator in logistics	HQ	GVN
11-0908	M	INGO	Senior management in logistics	HQ/National	LDN/SAN
12-1208	M	IFRC	Senior management in logistics	Regional	KYA
13-1208	F	IFRC	Mid-management or coordinator in programmes	National	Damascus
14-1108	F	UN Agency	Mid-management or coordinator in programmes	HQ/HQ/Reg	ROM/GVN/CHI
15-1908	M	IFRC	Mid-management or coordinator in programmes	HQ	Geneva
16-3008	F	INGO	Senior management in logistics	Regional	Nairobi
17-0109	F	INGO	Senior management in logistic	Nat	Bogata

Endnotes

1. SARS-CoV-2, a novel coronavirus (2019-nCoV), was first detected in Wuhan Province, China, in December 2019. Within three weeks there were 118,000 cases of the virus (renamed COVID-19), in 114 countries and 4,291 people had died (WHO, 2020).
2. (UNOCHA, 2020) Financing requirement as 4 Dec 2019: $28.8B to $39.39B (31 Oct 2020). Percentage of needs covered in Oct 2019: 53% to only 38% (Oct 2020).
3. 'Logistics' is used here to describe professionals within the humanitarian sector engaged in any area of supply chain management, and the name for this position alters between organisations. For the purposes of these interviews, participants were asked to identify from the following options: A) Midmanagement or coordinator in programmes or Mid-management or coordinator logistics, Senior Management in Programmes or Senior manager in Logistics, or Senior Leadership/Director.
4. The participants were asked to identify their organisation from a list of options: UN Agency /IFRC/ INGO/ National NGO or CSO/ Private Stakeholder.

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Social innovators as a human sensing network solving humanitarian challenges of the XXI century

By Matías René Rojas De Luca

Executive summary: Increasing complexity, and consequent heterogeneity, of societies prevents generalised top-down solutions from understanding in detail, and providing effective response, to problems arising. Empowering 'problem detectors-solvers' appears a feasible way to complement current efforts to solve complex problems through distributed solutions, offering an effective means to increase safety by improving social stability in Latin America. After analysing over 8,000 applications to open innovation challenges in Latin America, we have observed 12 clusters of socio-environmental impact initiatives, generating a distributed network of social innovators.

Tags: social innovation, social entrepreneurship, human sensing network, distributed solutions, open innovation, human sensors, Latin America, semantic analysis, clusters, Socialab

Section 1: Background and introduction

From 2019 to date, Latin America has experienced unprecedented social and political crises; the COVID-19 pandemic and an economic depression of great proportions, all under the shadow of the global climate crisis. During this time, creative and empathetic citizens detected problems 'in the field' and developed new products and services capable of solving some of these issues in real time. These include creating a machine that provides fresh water from air in remote locations; digital platforms that generate income for the elderly; and AI (Artificial Intelligence) powered software that keeps track of COVID-19 patients. They are known as 'social innovators' and have been able to mitigate negative consequences of these crises, contributing social stability in a convulsed region and providing safety measures to a huge, ad hoc complex system – Latin American society.

This case study has been developed together with Socialab, a Latin American impact accelerator and open innovation expert since 2012 with offices in six countries that provides data for the characterisation of social innovators.

The increasing complexity of societies and their consequent heterogeneity prevent generalised top-down solutions from providing an effective response to the problems that afflict them. In that context, empowering problem detectors and solvers appears to be a feasible way to complement current efforts from governments, enterprises, multilateral organisations and NGOs. Against complex problems, distributed solutions led by social innovators can increase safety by improving social stability.

From this reflection a key question arises: is it possible that the individual initiatives of social innovators in Latin America are attending common needs in several places at the same time and without top-down coordination?

Human sensing network

Social innovators have a particular way of sensing the world that differentiates them from other mechanisms in understanding social phenomena as they are capable of transforming day-to-day problems into opportunities and tend to act with creativity to solve them; in other words, "entrepreneurial or innovator action of any kind begins with the recognition of a problem." (Chavez et al, 2017)

As explained by Professor Nick Tyler[1], human sensors can be grouped in three types: i) physiological sensors, related to our body (as taste and sight); ii) environmental sensors, related to how we feel our context (as rhythm or time perception) and iii) interpretational sensors, regarding our perception of society (sense of justice, for example). These last types of sensors are particularly interesting, since they trigger innovators to solve a societal issue by considering their intrinsic motivation, not only explained by external stimuli, but also by the way they perceive reality and their will to modify it.

In that context, this case study intends to understand the ecosystem of social innovators in Latin America as a distributed network of sensors that can understand social issues efficiently and use their creativity and entrepreneurial capacities to solve them. Moreover, it aims to frame it under a complex systems perspective, which may allow it to map the network and suggest courses of action for improvement.

Section 2: Analysis and insights

Study framework

Due to the nature of the field of study and its difference to human engineered complex systems – such as the construction of a space shuttle – it is unlikely that we can understand this system only by applying the Safer Complex Systems (SCS) Framework (McDermid et al, 2020). Thus, social science tools were considered, using the Social Emergence Paradigm framework (Sawyer, 2005). Both frameworks are used to map the network of 'social innovators as a complex system'. The first framework allows us to characterise the complex system and the second one allows us to focus on the different layers of the complex system so we can suggest different courses of action for achieving successful outcomes, such as maximising social stability by providing new solutions for unsolved issues.

SCS framework

Although the analysed system is ad-hoc and not human-engineered, the SCS Framework is useful to define the main properties of this network of social innovators. This case study assumes that the system meets four main characteristics, as described below.

First, the social innovation ecosystem in Latin America can be considered a self-organised group of people[2] that share the common purpose of generating social impact using different tools and knowledge, without being specifically employed for that matter. It is their individual intrinsic motivation that enables them to act as unique sensors, and these will be considered as nodes of the system in this case study.

Second, as the ecosystem is physically and digitally well connected, from shared offices in coworks to online events, it is possible to detect coupled feedback regarding the stimuli delivered to and from nodes in the system. Once a positive or negative output is generated (for example bankruptcy of a start-up or a successful investment round), the nodes of the system react in non-linear and unpredictable ways. For example, repeating successful investment rounds once one of the innovators demonstrates that it is feasible[3].

Third, social innovators interact with different entities that support their development, from incubators to investment funds, allowing them to cross the semipermeable boundaries of the system. These interactions can change the course of social innovators' development from outside of the system[4].

Finally, the development of new products and services that generate positive social impact is the expected emergent property of the interaction of individuals that comprise the human sensing network.

The main components of the SCS Framework were applied to the system as presented in **Figure 1**, using the assumption that the main goal of this system is to develop and implement new products and services that may generate a positive impact on people suffering from different crises.

At the same time, this characterisation allows us to identify the cases where failure of the system happens, referring to the reduction or impossibility of the correct deployment of novel solutions in society. Some examples of these failures[5] are related to: negative effects of the solutions being implemented (. for example, generating disputes inside a vulnerable community when certain members are benefitting from having drinkable water, while others are not); regulatory prohibition to develop certain services (for example, fintech services that improve individual savings, but can't be implemented because of the lack of legal permits;) or bankruptcy of start-ups as governments take excessive time to pay for services that have already been provided (due to bureaucratic paperwork that has little to do with the quality of the service), among others.

The examples mentioned above raise safety concerns towards the risks in the system that can have negative safety impacts due to its complexity and have the potential to cause emergent safety consequences.

Therefore, the SCS Framework raises the question of how to develop measures that improve social stability through means that cannot be harnessed by governments, corporations or NGOs.

The exposed themes are intended to be addressed through the analysis shared in this case study, with the goal of describing the maximisation of safety parameters to build a successful safer complex system.

Emergence paradigm framework

The previous analysis is still insufficient to explain interactions and emergent properties of this social innovator network, thus it is necessary to appeal to social sciences to understand the social innovators ecosystem as an ad-hoc complex system that emerged through the interaction of innovators, with the goal of finally suggesting lever points that maximise the success of the system.

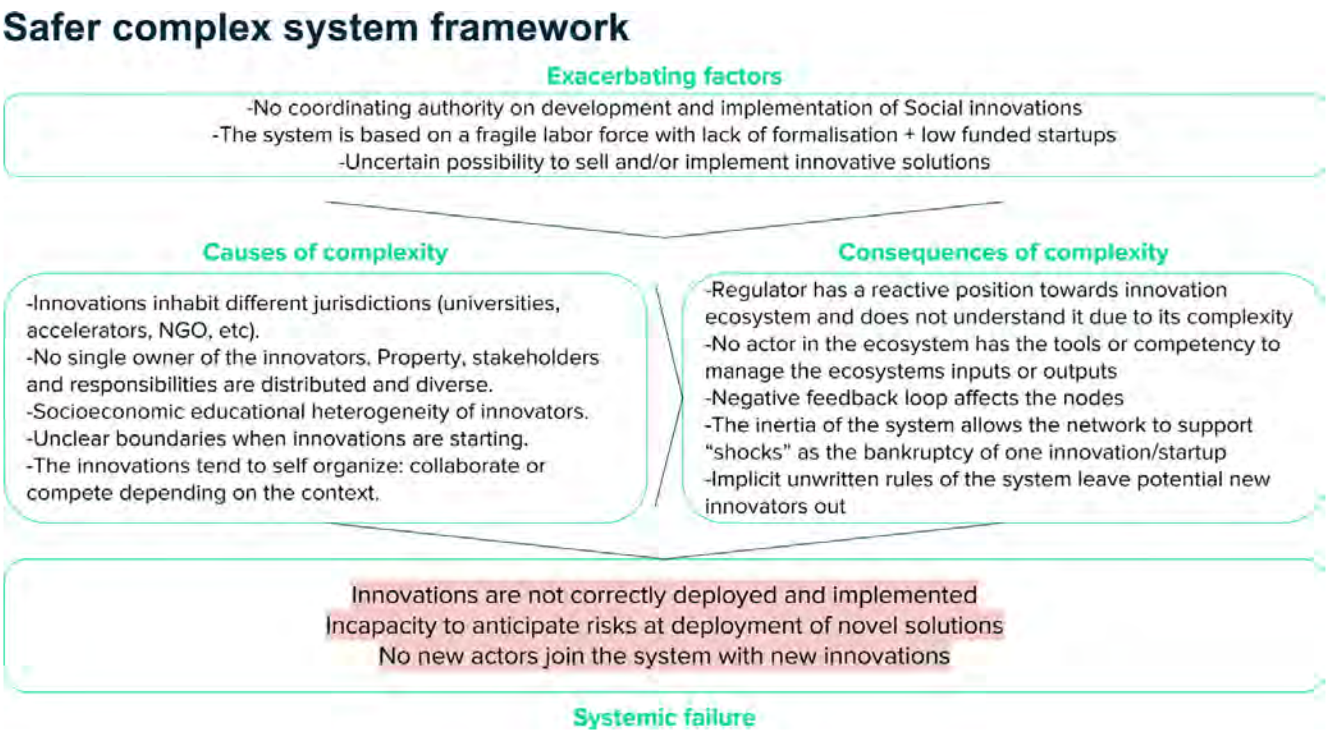

Figure 1: Social Innovators Complex System analysis under the SCS Framework. Details, causes and consequences of the complexity of this system with its exacerbating factors.

To perform the analysis, The Social Emergence Framework was used (Sawyer, 2005). The author sustains that the relationship between two levels, individuals and the social system that they compose is insufficiently explained by the Structure Paradigm that analyses the relationship of the social structure and individuals as a top-down causation where the behaviour of the last is determined by the imperant structure. On the other hand, the Interaction Paradigm – its antithesis – adds a new layer of analysis (interaction among individuals) and emphasises a bottom-up relationship, where individuals and interactions work as creative agents and determine the social structure. As both frameworks prove themselves incomplete, Sawyer suggests the Emergence Paradigm Framework, adding two new levels of analysis that take into account the emerging properties generated by the interactions of the individuals in the system so that, although the norms, laws and other structural elements are generated or inspired by their collective actions, at the same time this structure has causal power over the individuals and their interactions.

The five levels of this framework are described below and the application of the framework to the social innovators case is detailed on **Figure 2**.

- Level E – Social structure: Written texts that rule the system (procedures, laws, regulations); Material systems and infrastructure (architecture, urban design, communications and transportation networks).
- Level D – Stable emergents: Generated subcultures, slang and collective memories; conversational routines and shared social practices.
- Level C – Ephemeral emergents: Determined frame context or topic in which individuals interact; relative roles or status of individuals and their participation structure.
- Level B – Interaction: Symbolic interaction among individuals on the system; processes of collaboration, competition or negotiation; discourse patterns between them.
- Level A – Individual: Specific characteristics of the individuals as their personality, purpose, cognitive processes and specific capacities.

Figure 2 helps us understand the social innovators network as a system built upon five different levels from the social structure to the individual's characteristics, in particular focusing on Levels C and D where emergent properties appear.

This framework is relevant since it makes it possible to propose different leveraged actions and apply them in each level in order to maximise the probabilities of success of the expected emergent properties; moreover, it can allow us to understand how actors can traverse different levels to incentivise change that allows safer outcomes of the system.

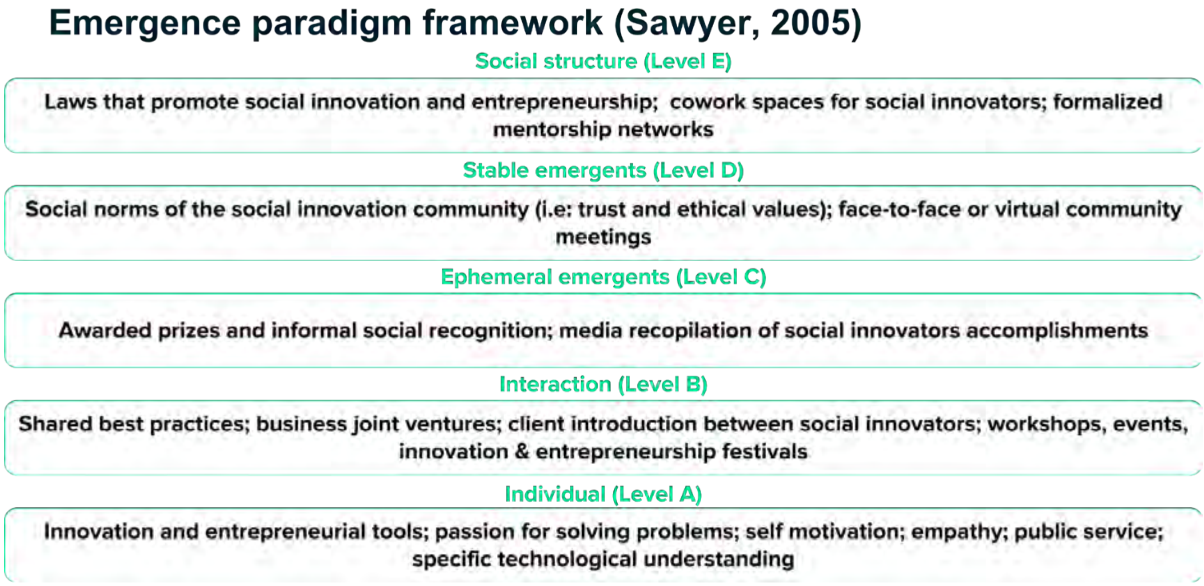

Figure 2: Social Innovators Complex System analysis under the Emergence Paradigm Framework, where the main elements of the system are grouped into five levels.

Available data

Socialab is a social enterprise that provides corporate venturing services to corporations and governments and works as an impact accelerator for start-ups. Through open innovation methodologies[6] Socialab has received more than 75,000 applications since 2012 from innovators in Latin America that have detected a problem and developed a solution.

The starting point for this analysis is a non-structured text database of applications received between 2018 and 2020 from 14 countries in Latin America, from which a subset of 8,353 entries from innovators who have uploaded their proposals was selected. For this case study, those entries and the innovators behind them are considered as the social innovators ecosystem. Additionally, the innovators were asked to answer a short survey for a deeper characterisation.

Results and insights

After conducting the survey and analysing the data from the proposals, it was possible to describe the findings in four main themes.

Theme 1: Understanding the human sensors, motivations and connections

With the goal of conceptualising the network as a complex system, a survey[7] was sent to and answered by a group of 171 social innovators. It covered questions related to their intrinsic motivations and their relationship with other innovators. All the responses correspond to Latin American-based social innovators and the three most represented countries were Chile (28%), Colombia (14%) and Argentina (5%), while the remaining 53% was distributed among 11 other countries. The main results are summarised below:

- Motivation: 33.9% of the respondents declared that their main motivation to solve social issues was the moral duty to contribute to society, followed by 19% who were motivated because of directly suffering from the problem and 18,4% who believed in social innovation as an interesting career path. On the other hand, 7.9% of respondents confirmed that they were motivated by their close circle of people. This answer reveals that of the subset of respondents, the main motivation was to identify a problem and act out of a strong sense of justice and solidarity.
- Needs: The respondents declared that their main difficulty in developing their innovation was access to funding (67.3%) and communication about their project (44.6%). On the other hand, 17.3% of respondents declared that they needed specific knowledge or expertise and 14.3% argued that they needed additional help to understand the problem. These answers give us a hint on measures that need to be taken to maximise the actions of these sensors.
- Recognised nodes: The survey asked respondents to identify the three most important social innovations in Latin America and the following are the five most frequently mentioned in the survey: *Algramo* with 20 mentions (start-up that reduces the use of plastic through bulk sale), *Greenglass* (reusing bottles by turning them into glasses), *Laboratoria* (training vulnerable women in programming tools), *Techo* (NGO that provides housing solutions and community development in slums) and *Balloon Latam*

Figure 3: word cloud of the most recognised social innovations in Latin America

(delivers entrepreneurial and leadership capabilities to rural communities). Figure 3 represents the frequency in which these initiatives were mentioned.

- Relationship with the network: Regarding the main reasons that make social innovators connect with each other in the ecosystem, the most mentioned were that they learn from their knowledge and experience (57.4%) and receive contacts that help them develop their initiatives (46.1%). 2.6% declared that they prefer working alone.
- Requirement for enabling interactions: From Socialab's experience regarding the relationships between social innovators, it is possible to witness that there is no formal contract or transaction that links them, but still, they generate collaborative interactions spontaneously. In that sense, different enablers are thought to be promoters of that collaborative culture: mutual inspiration, geographical closeness, related impact areas and trust, among others. This last one is particularly broad and interesting to understand. To deepen understanding about the meaning of trust in this context, a specific question was asked: "Identify the main characteristics that make other social innovators trustworthy.". As it was an open question, multiple answers where received, from which the most frequent are highlighted: evidence and transparency of the impact they generate; perseverance; coherence between what is said and done; empathy; genuine and unselfish desires to solve a problem; optimist vision; creativity; leadership; technical capabilities and closeness to the problem.

The results of the survey and its main conclusions allow us to conceptualise the network of social innovators in the form of nodes and links that shape to a complex system of sensors, as shown on **Figure 4**.

Theme 2: Mapping social innovations

Through the text generated by 8,353 applications received by Socialab and 24 open innovation calls from 2018 to 2020, it was possible to vectorise them into a 400-dimension space. Vectorisation was performed by using the machine learning algorithm word2vec (Mikolov, 2013), where semantic representations are learned from Spanish words using the full Wikipedia in Spanish[8]. To represent sentences, all words were averaged to compose each proposal after removing 347 stop words[9]. To visualise the proposals, we use a tSNE algorithm (Van der Maaten, 2008) to project proposals into a two-dimensional space in which each proposal is represented as a node on the graph in **Figure 5**.

The position of the nodes on the graph forms a graphical representation of the mapped social innovations where their proximity to other nodes represents a semantic similarity and their position on the graph represent distance units between them, not making reference to specific measurements (meters, pixels, etc).

Vectorial representation of innovations allow us to define a cluster hierarchy by using a Dendogram procedure. The above-mentioned algorithm revealed 12 areas of impact that the innovations addressed. After that analysis, each cluster was named by the analysis team, taking into account the main concepts and related words presented in **Figure 6**. It was possible to determine which subgroups of social innovators aim to solve different problems. Considering our initial premise, it appears that due to the topics discovered, the network of social innovators can also be understood

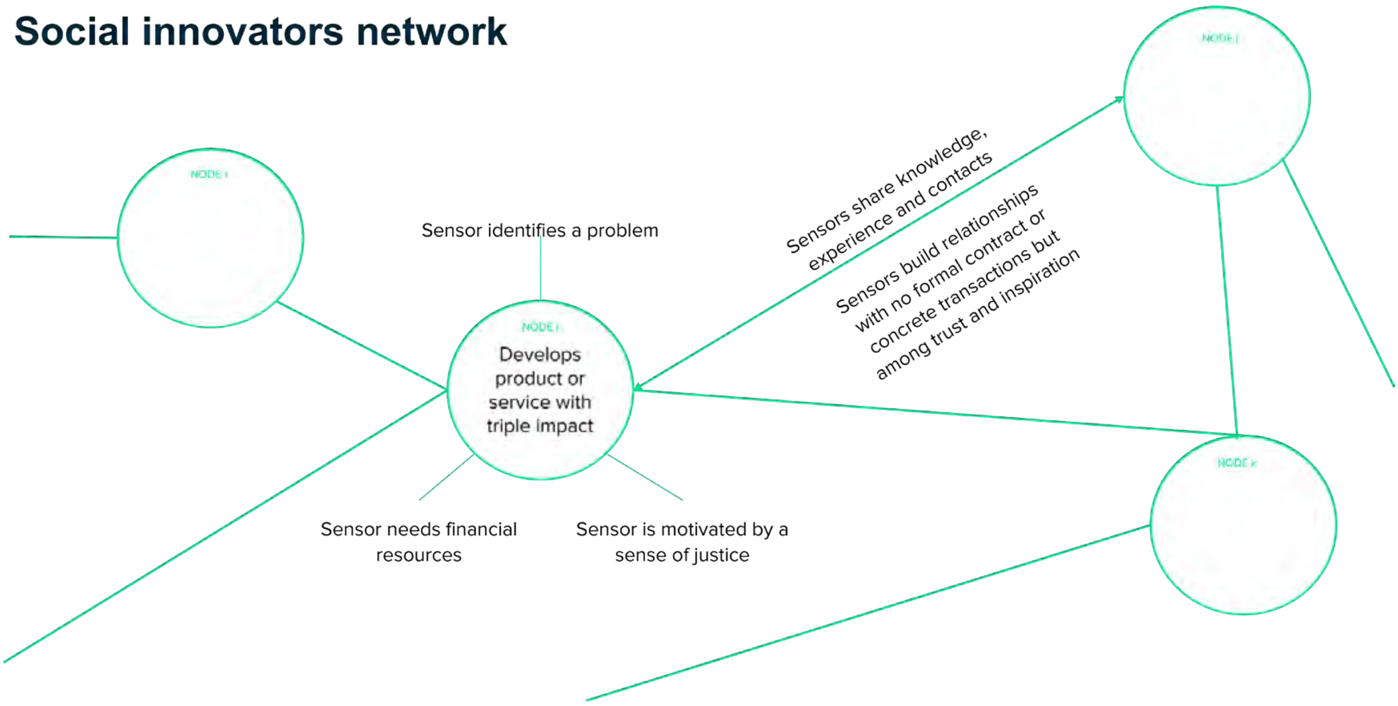

Figure 4: representation of the social innovation ecosystem as a complex system where each node represents a social innovator.

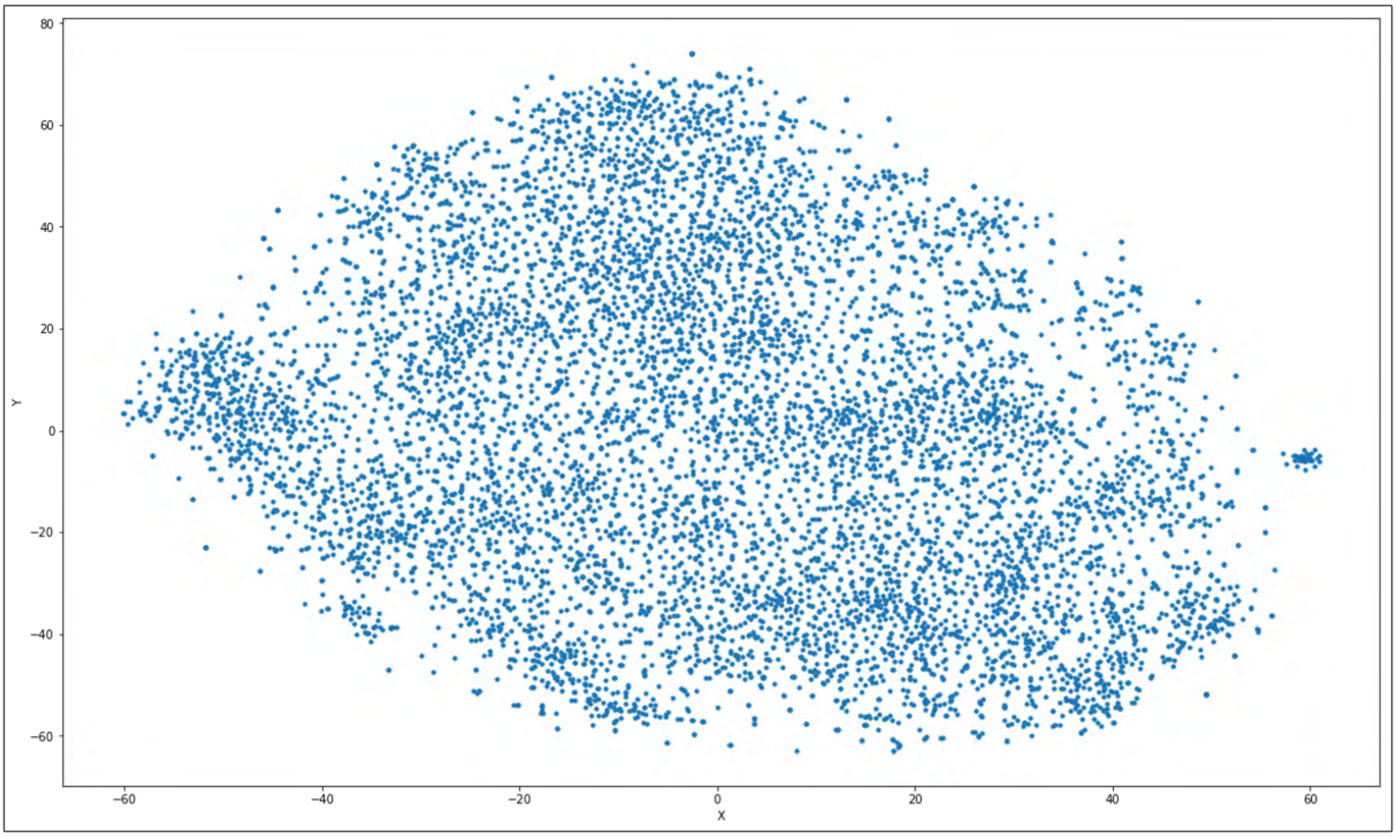

Figure 5: representation of the 8,353 nodes of the social innovation ecosystem in a two-dimensional space.

Figure 6: representation of the clusters found that group the main themes social innovators aim to tackle.

as an additional safety net to traditional mechanisms (for example public policies) that aim to design and implement new products or services to improve twelve pain points in society that these human sensors detect as relevant and actionable.

Performing a further analysis, it is possible to determine similarities between clusters that were grouped according to four major themes of socio-environmental challenges, as seen in **Table 1**. In the same table, it is possible to appreciate the frequency of each cluster, allowing us to understand what could be the most pressing issue that innovators sense and try to solve through their proposals, where the environmental (2,787) and the economic reactivation (2,425) themes represent the majority of proposals, followed by inclusion (2,090) and education themes (1,021).

Each of the 12 clusters has a centroid that represents the social innovation that best fits the cluster according to the text that describes it. In **Figure 7**, it is possible to see the distance between a particular idea and the centroids of each cluster. In this example, Servisenior is an online platform that connects older adults with micro tasks that generate them monetary income. It belongs to cluster 6 (red) and is nearer to clusters 4 (dark green) and cluster 2 (dark blue).

Table 2 shows an example of the word cloud generated from cluster 2 – inclusion of older adults – in Spanish. Highlighting the most frequent words and the identification (ID) of the centroid node.

Theme 3: Distribution by year and sex

To understand the evolution of the issues sensed by the network every year, the percentual change of each cluster was compared for each of the three years in which proposals were received. As shown in **Figure 8**, the amount of received ideas varies mainly in three clusters: i) constant increase of proposals in the pollution reduction cluster from 2018 to 2020; ii) significant increase (2% to 12%) in support for SMEs from 2019 to 2020, probably related to the economic crises derived from the COVID 19 pandemic; iii) the significant reduction of social clusters 2 and 8 from 2019 to 2020.

Though it is not possible to determine correlation or predictive capacity of social innovators and the main challenges society faces, it is interesting to analyse how these sensors perceive the change of priorities each year.

Other variations are not significant and can be attributed to biases induced by the title or theme of each open innovation challenge.

Additionally, a similar analysis was performed regarding the gender of social innovators and their presence in the different clusters, as shown in **Figure 9** as the number of innovations proposed by men (M) and women (F). The undetermined gender is

Environmental clusters	Inclusion clusters	Economic reactivation clusters	Education clusters
Pollution reduction (C1=1,313)	Inclusion of older adults (C2=1,268)	Development of tourism (C3=477)	21st Century Skills for Youth (C5= 549)
Environmentally sustainable businesses (C10=755)	Child-adolescent vulnerability (C8=822)	Modernization of the labor market (C4=782)	Digital literacy and digital tools (C6 = 472)
Generation of renewable energies (C11=367)		Generation of jobs and increase of income (C7=431)	
Recycling and reuse of waste (C12=352)		Support for SMEs (C9=735)	
2,787 total proposals	**2,090 total proposals**	**2,425 total proposals**	**1,021 total proposals**

Table 1: 12 clusters of impact areas in four main themes (# of proposals)

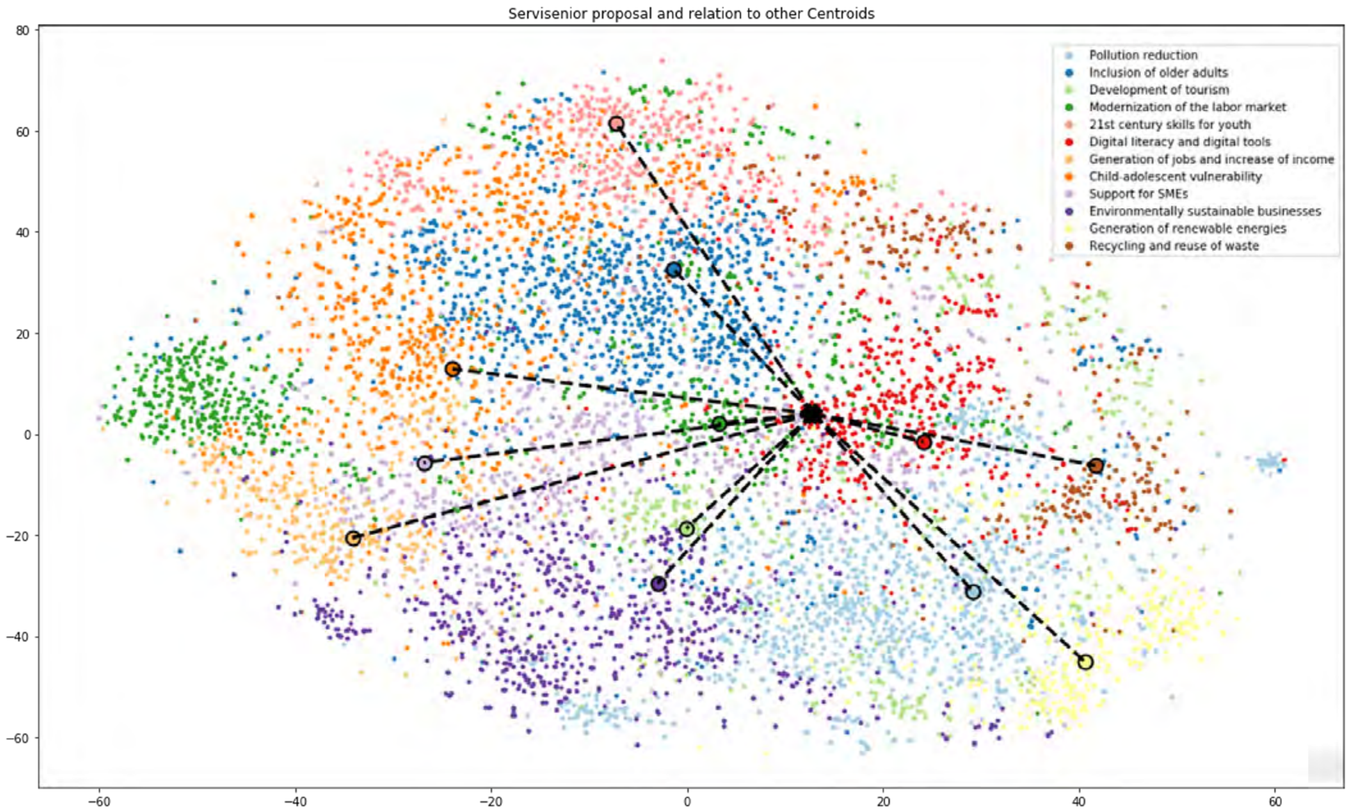

Figure 7: distance between a specific node (Servisenior = ID 120382) and the 12 centroids

represented with a letter A which could not be detected by the algorithm that had higher than 90% accuracy on assigning sex through names.

Using this gender estimation, it can be seen how certain topics are mostly proposed by women (child and adolescent vulnerability, inclusion of older adults), and others by men (reduction of pollution, modernisation of the labour market or support for SMEs).

Theme 4: Limitations of the clustering

The 24 open innovation calls from which the analysed proposals come had different themes through which social innovators were invited to upload their ideas. Though most of them aimed for a broad set of problems to be solved, for example How to live well for 100 years, some looked for specific solutions, such as Chile Breathe which searched for mechanical ventilators to support COVID-19 patients. In particular, only three of the 24 challenges have

Word cloud (Spanish)	Top frequent words	Centroid nodes
	1. Mayores (elder) 2. Adultos (adults) 3. Salud (health)	• 103598[10]

Table 2: details of cluster 2

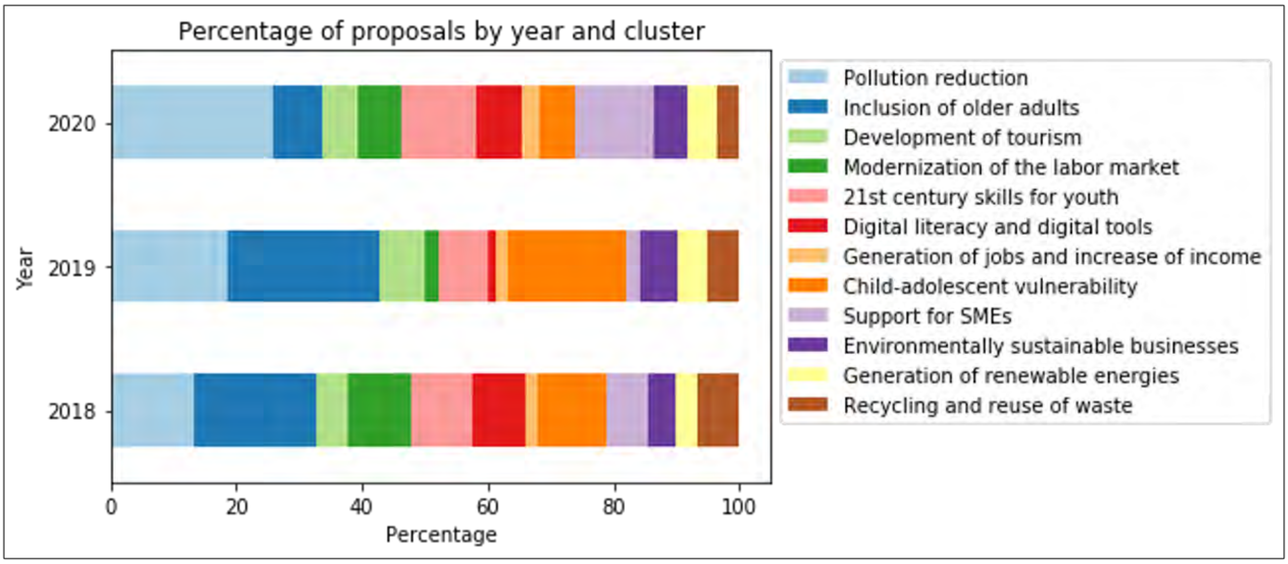

Figure 8: distribution of ideas received per cluster every year

less than six clusters represented, which invites us to think that the differences in the calls, given the high number of proposals, might not have relevant biases between years nor challenges regarding their representativeness in the clusters. The mentioned challenges are presented in **Figure 10**.

Although the analysis shows high diversity, it is not possible to conclude that the innovation calls are totally unbiased due to the following reasons: socio-demographic composition of the users of the challenge platform and Socialab's social networks might be targeting a certain archetype of social innovators; the difference in the incentives for each challenge might be focusing on certain types of innovations (i.e. software); lack of focused challenges on hard-to-tackle issues may be preventing the reception of proposals related to government corruption or geopolitical conflicts, among others.

Nevertheless, the current analysis of the social innovators ecosystem is based on a broad and representative spectrum of innovations in Latin America which allows us to draw conclusions within the mentioned limits.

Section 3: Discussion and transferable learnings

Key findings

Using the proposed frameworks, it was possible to conceptualise

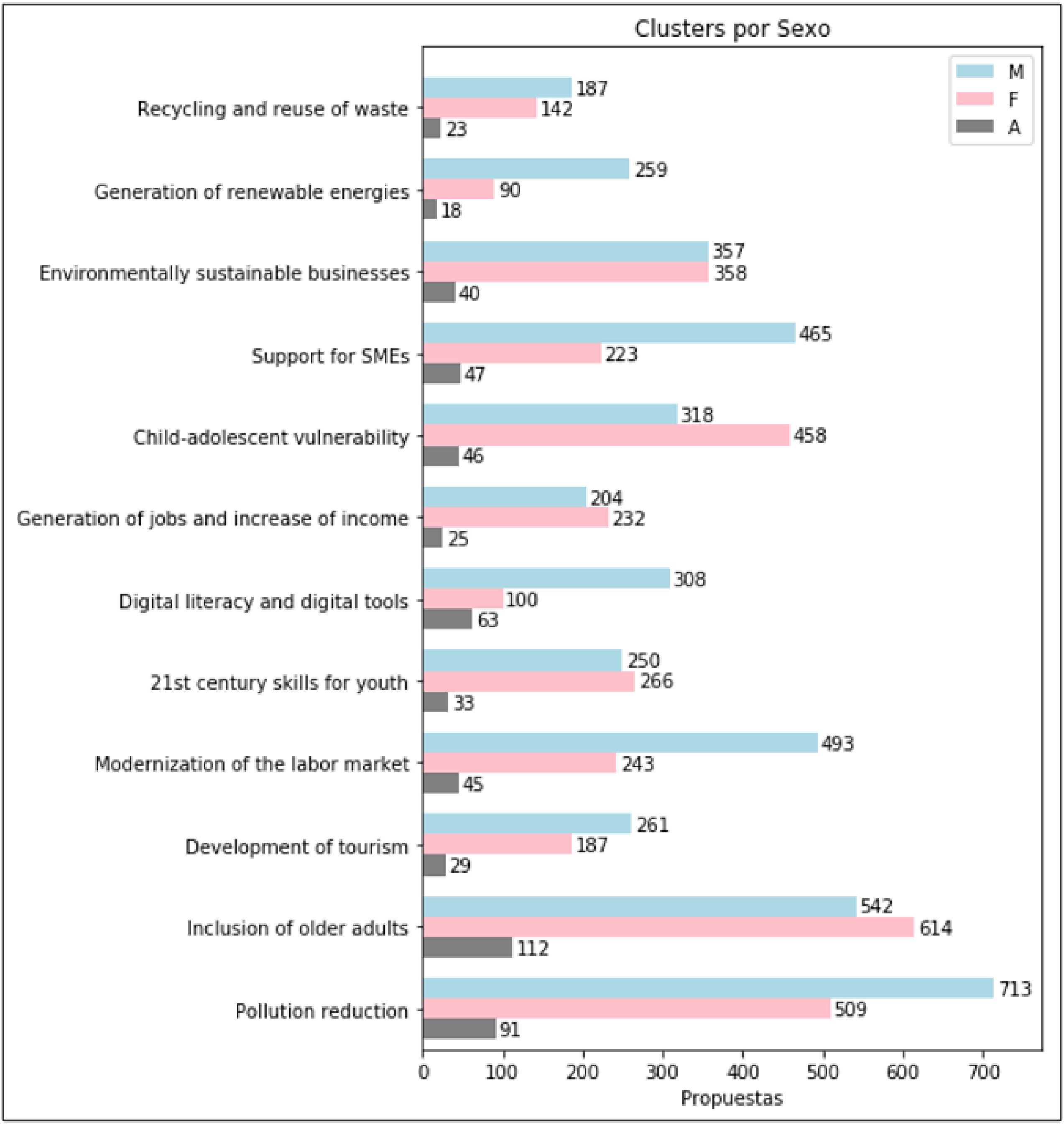

Figure 9: distribution of clusters per gender

this civic society response to social issues as a complex system of human sensors that are able to understand and decode the sophisticated and heterogenous problems of modern societies and can work as a massive and autonomous social impact research and development department.

Despite the great diversity of innovations on different topics, it was possible to narrow down the proposals to 12 areas of socio-environmental impact detected by these sensors. The clusters give us a thermometer of the main priorities that a segment of the citizenry detects and acts on. Additionally, variables such as gender and the year of application can vary the relevance of the different detected issues and thus could be considered to complement actual tools as surveys or impact studies.

The links between the nodes represent the interaction between social innovators and can be a key to strengthening the network. General topics appeared as relevant variables that could determine the state of the relationships as: interchange of knowledge; perception of trust; sharing of contacts; and financial support.

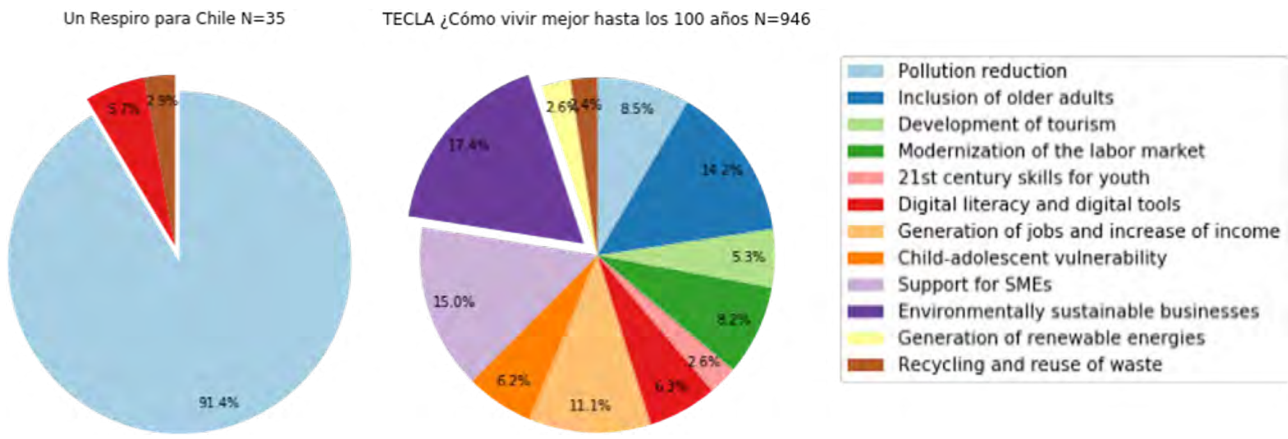

Figure 10: distribution of clusters in two different challenges to understand potential biases regarding the topic of the open innovation challenge.

Additional actors in the social innovation ecosystem must be considered when this complex system is mapped because semi permeable boundaries allow interactions that can deliver or take valuable resources to and from the system as investment funds, accelerators, government agencies and enterprises, among others.

The social innovation ecosystem is still working in silos in the sense that each innovator, incubator or investment fund, among others, pays attention to their own limited field of work and does not necessarily use a systems perspective that would allow them to increase the connections shown in Figure 4 to promote the success of the whole system. These actors are still lacking concrete actions that remove barriers to collaboration and enriching the links between nodes, for example sharing good practices among incubators, co-investing in start-ups or unifying impact measurement.

Aiming for a safer complex system

The prevention of systemic failure by increasing safety of the system is referred to as allowing a fertile ground in which innovators can create, connect with others and have the necessary tools to ensure positive impact once their new products and services are implemented; not only focusing on this last output but also on the whole innovation process, from initial motivation and problem sensing to technical capabilities for correct implementation.

On the other hand, social innovators and their solutions play an important role in solving issues that other actors, such as governments, corporations or NGOs, cannot tackle because of their advantages in agility and speed on sensing and solving problems. Therefore, they contribute to social stability in convulsed societies, building safer complex systems.

To ensure safer outcomes, different design and operation controls are proposed within the leverage points of the system, outlined below.

Understanding the leverage points of the system

Using the Emergence Paradigm and applying the key learnings from the survey and clustering analysis, we can identify five types of leverage points categorised within the levels explained in section 2.

The proposed leverage points that are shown in Table 3 were developed through a Systems Aikido perspective (Webb et al, 2010). This proposes the constant redesign of the system by redirecting its own momentum and self-organisation properties to generate change with minimal energy expenditure in opposition to 'brute force' that attempts to control several inputs over the system with great effort, being often insufficient when dealing with the complexity of social systems.

Conclusion

Understanding this global network of sensors and innovators represents an opportunity to enhance another line of defence against the problems that the public, private and third sectors have not able to tackle in the dawn of the 21st century.

This overview of complex systems incorporated into the Latin American social innovation ecosystem allows us to reveal a hidden force that, starting from civil society, intends to face relevant and actionable challenges. This ad-hoc system of human sensors is yet an invisible force, complementary to governments, enterprises and NGOs and capable of detecting problems and generating solutions individually, while at the same time promoting itself as a large thematic research and development department of social impact that contributes to bringing social stability to one of the regions most affected in the world by the COVID-19 pandemic.

Furthermore, the vision of safer complex systems allows us to

Levels	Suggested leverage actions to be taken
Social structure (Level E)	1. Governments and other institutions officially acknowledge, validate and communicate evidence of impact generated by social innovators. 2. Promotion of focalized policies by gender according to the area of impact to be promoted. 3. Deliver financial resources to specific clusters so they can accelerate the test and implementation of social innovations.
Stable emergents (Level D)	4. Consolidate, communicate and periodically update social norms agreed upon the nodes of the system in a code of conduct.
Ephemeral emergents (Level C)	5. Create awards for measurable impact from social innovations, not only their *elevator pitches*[11]. 6. Encourage transparency among impact indicators to foster trust among social innovators.
Interaction (Level B)	7. Reinforce and promote channels and interactions that foster the mutual admiration and inspiration feedback loops between nodes. 8. Implement peer to peer revisions of risks matrix of innovations prior to their implementation.
Individual (Level A)	9. Reinforce the sense of justice social innovators have and channel that energy towards the possibility to create new products and services. 10. Communicate to social innovators that they are part of a system and that there are others like them with a similar purpose. 11. Reinforce already existing empathy through cultural change campaigns.

Table 3: Suggested leverage points to maximise systems outcome

understand that for the socio-environmental problems we face today, there are no problems to solve, but rather systems to be optimised.

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Endnotes

1. Information raised during an online conversation taking place in April 2020.
2. As reported by Socialab's accelerators specialist, during acceleration Bootcamps each of the 24 cohorts of selected start-ups from 2018 to 2021 have generated spontaneous and unplanned activities and interactions as: informal meetings, networking sessions

or formal workshops, sharing their knowledge among others.

3. After the $85MM USD investment in NOTCO in 2020 (vegan food producer that lowers CO_2 emissions), a series of new investment rounds have been raised by Chilean start-ups for more than $200MM USD until April 2021. That shows a 'snowball effect' in the social innovation ecosystem (Article in La Tercera, Chilean newspaper in Spanish).
4. Since 2010 at least 15 high impact accelerators have been created to transfer economic resources and knowledge (Article in Latinamerican Reports).
5. Declared by Socialab's accelerators specialist through a virtual interview.
6. Open innovation methodology consists of the posting of an online challenge with the invitation to contestants to solve a socio-environmental problem, offering an award to the best innovations.
7. The summary of the survey in Spanish can be seen in the following link and was only sent to Spanish speaking countries (Brazil was excluded from this analysis).
8. The analysis excludes applications in Portuguese; thus, Brazil is not included in this case study.
9. Common words that don't add valuable information to the analysis, mainly articles.
10. Identification number given to each of the analysed proposals (applications).

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Improving resilience to major safety events by analysing case studies

By Prof Richard Taylor MBE, Dr Neil Carhart, Dr Graeme Collinson, Richard Voke, Dr John May, Dr Andrew Weyman

Executive summary: Development of a potentially widely applicable 'tool' to address sometimes neglected 'organisational and cultural' precursors to major safety-related 'events' is described. Twelve 'events' across several industries were studied, and detailed 'expectations of good practice' developed. Associated 'penetrating diagnostic questions' were also then developed to enable the identification of potential operational vulnerabilities, and a 'systems approach' is outlined (which also addresses behavioural factors) to facilitate the design of effective interventions.

Tags: Ramsgate walkway collapse, Heathrow Express tunnel collapse, Longford Gas Plant explosion, Tokai-mura criticality accident, Davis-Besse nuclear reactor incident, Columbia shuttle disaster, Paks nuclear plant fuel accident, Texas City refinery accident, Buncefield fuel storage explosion, Nimrod aircraft crash

Section 1: Background and introduction

Events such as a space shuttle disaster, oil refinery accident and the collapse of a pedestrian walkway may appear to have little in common. Such events have occurred in different industrial settings, involved very different engineering failures, and have happened in different operational contexts. However, analysis of the findings from the investigations that took place following twelve disasters that occurred across a wide range of 'high hazard' industries, reveal significant similarities in their deeper-lying organisational and cultural accident precursors.

An important conclusion is that if defences can be developed to remove or mitigate these vulnerabilities, they should enhance organisational resilience to accidents across a very wide range of industrial settings. Effective use of this learning could reduce the occurrence of major events which have, in some cases, cost many lives and led to significant environmental damage – as well as financial loss, reputational damage and impacts on infrastructure.

It is important that greater awareness and understanding of organisational and cultural precursors in the causation of major events and their similarities is fostered among relevant stakeholders, including policy makers, corporate leaders, regulatory bodies and other safety professionals. This paper aims to help achieve this and outlines how, following encouraging foundation research (1,2) and more recent work (3) funded by the UK Energy Institute (EI), an approach is being developed which offers the prospect of identifying and then more effectively addressing these precursors to failure which should be of value to both operational organisations and their regulatory bodies.

The analysis is based upon the major events listed in **Table 1**. These events were chosen following discussions with relevant industry sectors about key sources of potential learning, taking into account the depth of investigations and the extent to which they identified and considered organisational and cultural deficiencies. The analysis of the case studies is intended to provide a contribution to learning and not criticism of the organisations involved.

Two further events (the Deepwater Horizon accident in the Gulf of Mexico in 2010, and the Fukushima nuclear event in Japan in 2011, have been the subject of preliminary study and many of the organisational and cultural precursors were found to be similar to those in the events above.

Following most of the events, considerable efforts were made by some organisations and regulatory bodies to apply the learning, but this was typically restricted to the specific industry sector directly involved. Furthermore, findings were often addressed on a fragmented, one-by-one basis without considering the potential systemic 'knock-on' effects which arise in a complex system. Major events continue to occur with, for example, a very high number of large losses in the energy industry reported since 2017 (4).

Table 1 – case study major events and key investigation references

Ramsgate – walkway collapse, UK 1994	Health and Safety Executive, 2000a, 'Walkway Collapse at Port Ramsgate: A Report on the Investigation'.
Heathrow Express – NATM tunnel collapse, UK 1994	Health and Safety Executive, 2000b, 'Collapse of NATM Tunnels at Heathrow Airport: A Report on the Investigation'.
Longford – gas plant explosion, Australia, 1998	Royal Commission, 1999, 'The Esso Longford Gas Plant Accident: Report of the Longford Royal Commission' and, 'State Coroner Victoria Inquest into the Deaths of (named individuals) and the Fire at Longford Gas Plant Number 1'.
Tokai-mura – JCO criticality accident, Japan, 1999	IAEA, 1999, 'Report on the Preliminary Fact-Finding Mission Following the Accident at the Nuclear Fuel Processing Facility in Tokai-mura, Japan', Vienna, Austria.
Hatfield – railway accident, UK 2000	Office of Rail Regulation, 2006, 'Train Derailment at Hatfield: A Final Report by the Independent Investigation Board'.
Davis-Besse – nuclear reactor incident, USA, 2002	US Nuclear Regulatory Commission, 2002, 'Davis-Besse Reactor Vessel Head Degradation Lessons-Learned Task Force Report'.
Columbia – shuttle disaster, USA, 2003	Columbia Accident Investigation Board, 2003, 'Columbia Accident Investigation Board Report', Washington D.C.
Paks – nuclear plant fuel accident, Hungary, 2003	IAEA, 2003, 'Report of the Expert Mission Conducted Under the IAEA Technical Co-operation Project', HUN/9/022.
Texas City – refinery accident, USA 2005	Chemical Safety Hazards Investigation Board, 2007, 'Investigation Report: Refinery Explosion and Fire', Baker et al, 2007, 'BP U.S. Refineries Independent Safety Review Panel', and BP interim 'Fatal Accident Investigation Report', May 2005.
Thorp – reprocessing incident, UK 2005	Health and Safety Executive, 2005, 'Report of the Investigation into the Leak of Dissolver Product Liquor at the Thermal Oxide Reprocessing Plant (THORP), Sellafield'.
Buncefield – fuel storage explosion, UK 2005	Buncefield Major Incident Investigation Board, 2008, 'The Buncefield Incident, 11 December 2005 – The Final Report of the Major Incident Investigation Board'.
Nimrod – aircraft crash, Afghanistan, 2006	Haddon-Cave QC, 2009, 'The Nimrod Review – An Independent Review into the Broader Issues Surrounding the Loss of the RAF Nimrod MR2 Aircraft XV230 in Afghanistan in 2006', Published. by HMSO.

The present research has been taken forward (1,3) in three iterative steps:

Step 1 involved synthesising findings from the twelve events to form a basis for producing a set of initial organisational 'expectations' of good practice specifically aimed at promoting higher resilience to failure. These have been presented in the form of statements against which organisations should be able to benchmark their equivalent requirements and should enable potential 'gaps' (potential vulnerabilities) to be identified. If organisations do not currently have such statements, those developed provide a possible template.

Step 2 relates to work recently carried out, to generate from the expectations, sets of 'penetrating diagnostic questions' as part of the work funded by the UK Energy Institute (to be published). These are designed to help duty-holders determine the extent to which expectations are being met in practice in their organisation. It is vital to assess the strength of this link between 'aspiration and reality' – the need for intentions to be 'embedded in the bloodstream' of the organisation. Successful prototype work with Centrica plc on this topic (5) was carried out to test the approach.

Step 3 involves work which is currently underway. When expectations are found not to be realised in practice, organisations need to design effective interventions to address the vulnerabilities identified. It is important that planned interventions do not produce unanticipated and undesirable secondary knock-on effects (such as suppression of reporting, or over bureaucratisation of procedural requirements) and an approach is being developed which should minimise this. Importantly, this will also incorporate 'behavioural' and socio-technical elements.

Some of the key benefits of the approach include:

a) A means of achieving a

systematic risk assessment of the sometimes neglected organisational and cultural precursors to failure complementing well-established tools (such as Probabilistic Risk Assessments and Hazops) which enable engineering vulnerabilities to be assessed;

b) The potential to improve safety in processes involving complex interactions between people, processes and plants across a wide range of industry sectors – enabling and encouraging wider learning;

c) An approach which should be practical in its application and raise awareness of 'operational reality' at all organisational levels through the application of the 'penetrating diagnostic questions' and to address them through team collaboration;

d) A process which should be widely applicable and robust, yet sufficiently flexible and manageable to meet the needs of organisations across the spectrum of capability and organisational maturity. It should enable either analysis of specific areas of concern, or a review across all areas to be carried out, and;

e) It should reduce the tendency to employ a 'piecemeal' approach to designing interventions to reduce vulnerability to events. It enables potential responses to be designed holistically as part of a systems approach, 'rehearsed' and analysed with the involvement of those involved in the change – enabling potential 'behavioural' factors to be recognised and addressed.

Section 2: Analysis and insights

2.1 Event findings and the choice of 'themes'

Findings from the review of the twelve events have been categorised under ten broad and often inter-related 'themes' and sets of expectations developed within each. **Figure 1** illustrates the relationship between the themes in an organisational setting. However, it is important to note that in order to draw out the systems implications and the potential complexity involved, it is necessary to develop a more detailed 'causal understanding' (see Section 2.2).

Table 2 attempts to provide an indicative overview of the extent to which elements of each theme were identified in the findings from each of the twelve events. It shows that a high proportion of the investigations identified factors within all themes. It is a matter of judgement as to the degree of importance attached to each entry in the table, but some indication of this has also been given based on the respective investigation reports.

A very brief outline of the themes is presented here, but a full discussion of each of these and their basis can be found in reference 3.

a) Business environment

What has been referred to as the 'business environment' (e.g., the need to complete a project to a very tight schedule or the impact of major organisational change on operations) was present and led to unintended consequences to varying degrees in all of the events studied. Under such circumstances, achieving greater resilience requires leadership awareness of potential impacts on safety, reinforced by a rigorous management of change process that identifies and effectively mitigates the potential impact of proposed changes on safety. This needs to be independent and effective, or there is a danger that decisions may simply be 'rubber stamped'.

b) Leadership

It is vital that competent, well-informed senior leaders 'set the tone at the top' and that this is reinforced by actions and visible commitment. As depicted in **Figure 1**, the role of leaders is primarily to develop organisational strategy, establish requirements and provide oversight; whilst that of operational management is to ensure full understanding and effective implementation and monitoring. At all levels of leadership, a vital objective is to promote attitudes and behaviours, provide resources conducive to maintaining high standards and to achieve the motivation and involvement of all staff to seek continuous improvement.

c) Safety culture

All of the events studied exhibited shortfalls in safety culture. Examples include:

- A lack of commitment and operational awareness among leaders;
- Failure to learn from experience;
- A tendency towards 'operational drift' where poor practices become the norm;
- The absence of a sufficiently questioning attitude and 'precautionary' approach to emerging risks and rigour in addressing them;
- Failure to involve the workforce in identifying and implementing improvements.

d) Safety Management System (SMS)

Good safety performance requires the presence of an effective SMS that sets out the required approach to all important operational matters – including defined performance standards, making accountabilities clear and providing the workforce with understandable and practicable procedures to enable risks to be effectively controlled. In **Figure 1**, some themes have been grouped under the general heading of the SMS as these must be supported by clear organisational systems to provide a basis for

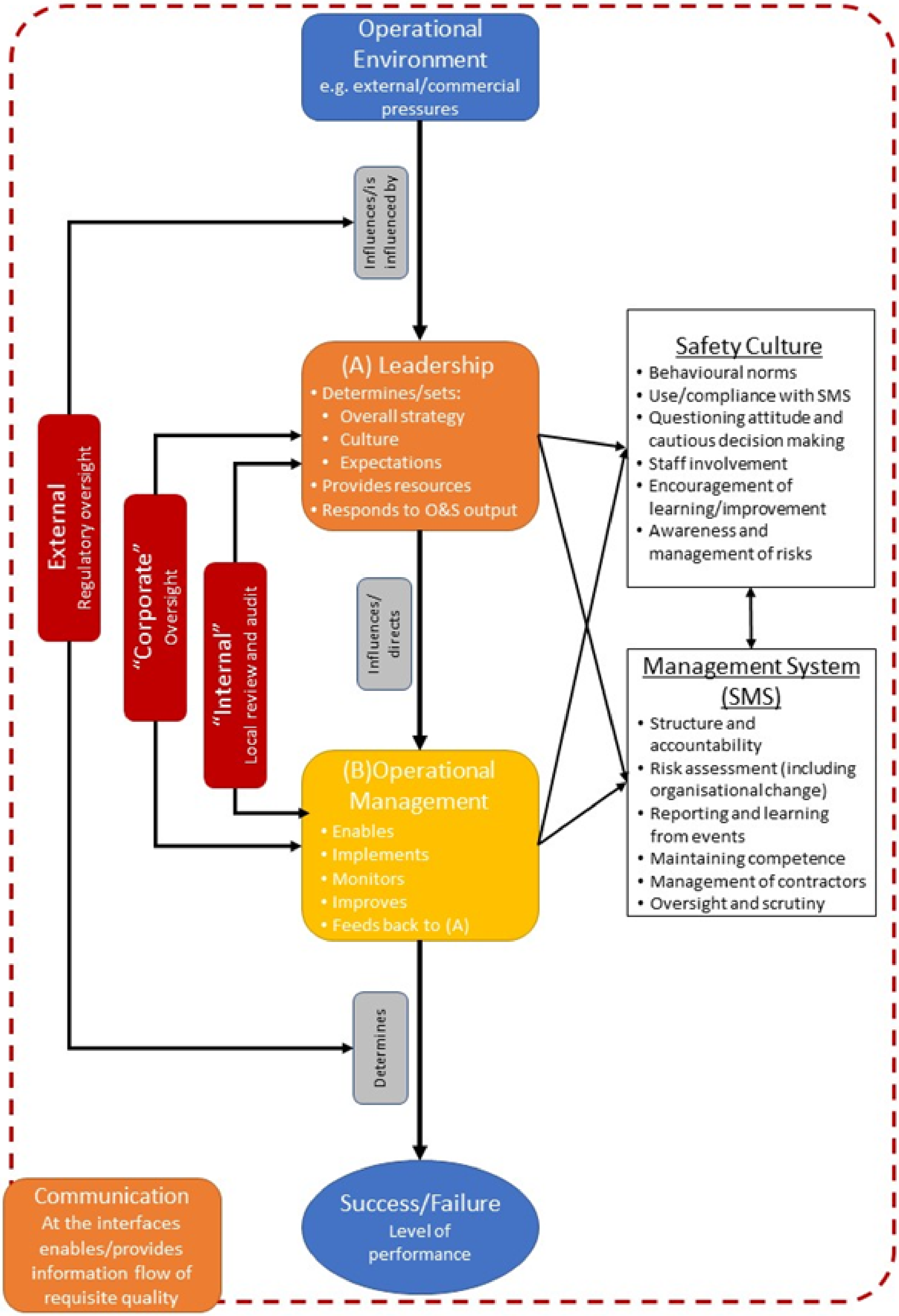

Figure 1 – the relationship between the themes in an organisational setting

Table 2 – indicative overview of the extent to which elements of each theme were identified in the findings from each of the twelve events

	Themes									
Event	**Leader-ship**	**Safety Culture**	**Business Environ-ment**	**Comms**	**SMS**	**Risk Assess-ment**	**Repor-ting / Learning Organ-isation**	**Compe-tence**	**Contractor Manage-ment**	**Over-sight and Scrutiny**
Longford	**	**	*	**	**	**	**	**	x	**
Texas City	**	**	**	**	**	**	**	**	x	**
Buncefield	**	**	**	**	**	**	**	**	**	**
Tokai-mura	**	**	**	**	**	**	*	**	x	**
Davis Besse	**	**	**	*	**	**	**	*	x	**
Paks	**	**	**	*	**	**	*	*	**	**
Thorp	**	**	*	*	**	**	**	**	x	**
Ramsgate	**	**	**	**	**	**	*	**	**	**
Heathrow	**	**	**	**	**	**	**	**	**	**
Hatfield	**	**	**	**	**	**	**	**	**	**
Columbia	**	**	**	**	*	**	**	*	**	**
Nimrod	**	**	**	**	**	**	**	**	**	**

Notes:
** Aspects relating to these 'themes' appeared to be significant precursors to the event.
* Contributory factors mentioned or strongly implied in relevant investigation reports.
x Not apparently applicable to the event.

effective implementation. However, they are important topics in their own right, that require in-depth consideration and have therefore been identified as separate themes.

e) Risk assessment and management

Shortcomings identified in assessing and managing risks ranged from failing to take a 'holistic' view of risks to deficiencies in 'day-to-day' operational risk control. In the latter case, there was often a lack of awareness and/or competence, and sometimes a failure to recognise the need to continuously monitor and seek expert advice when necessary. This was found to be particularly important for new plant, processes or systems and during recognised higher risk phases of work – such as start-ups.

f) Reporting and learning

A 'learning organisation' first needs effective reporting of precursors to failure based on a well-understood and accepted 'just' system. Leaders and managers need to make it clear through their response and resulting actions that feedback from staff and wider learning from events is highly valued. Underpinning this process is the need for organisational arrangements to ensure that effective learning is developed and disseminated to those who can benefit, in an accessible form which recognises the context of the potential area of application. It is very important that learning is made available wherever it may have relevance and that effectiveness in its use is assessed.

g) Competence

Shortcomings were also found to have arisen, at least in part, by failure to provide systems to ensure personnel competence and effective associated training at many levels in the organisations involved. In addition to competent and up-to-date coverage of technical matters, there were often shortcomings in ensuring that organisational, cultural and 'people issues' received adequate emphasis and, importantly, that training fully reflected operational reality. Maintaining competence within relevant functions during organisational change, ensuring continued understanding and compliance with changes in procedures and maintaining a capability to detect emerging risks, were also identified in several events as being particularly important.

h) Contractors

Not all of the events studied

involved contractors. However, where they did, deficiencies at the interface between the duty-holder and contractors were often very significant. These included:

- Poor communication and project control;
- A lack of clarity about operational procedures between organisations;
- Contractual arrangements which resulted in failures to report deficiencies, and
- A failure of the client to retain the motivation and capacity to understand and scrutinise contractor work (i.e., failure to act as an 'intelligent customer').

i) Communication

Failures of communication were identified across a wide range of organisational interfaces in the events studied and because of its all-pervading importance, it is represented separately in **Figure 1**. Failures ranged from ineffective engagement by leaders to obtain sufficient understanding of 'operational reality' with breakdowns in communication both up and down the management chain, to failures of communication at important interfaces such as that between client and contractor, and within and between teams. There were many examples of deficiencies at shift hand-over, and between operators and support functions. In some cases, communication was inhibited by over-complex or bureaucratic organisational arrangements.

j) Oversight and Scrutiny (O and S)

Shortcomings in O and S ranged from a lack of recognition that operational monitoring and audit requires effective organisational arrangements and a willingness to challenge existing, and sometimes well-established, practices to the need for the wider organisation to maintain an effective process for 'independent' oversight (usually by a dedicated corporate safety function). Having such safety processes enables senior leaders to maintain a stronger awareness of emerging risks and for them to use the results, together with analysis of trends and open feedback through the management chain, to obtain a regular overview of safety performance, and to take appropriate action to prioritise and address identified deficiencies.

The ten themes identified here align with many of the factors in the initial University of York Safer Complex Systems (SCS) Framework Report (6) and, as concluded in Section 3 below, use of the findings from this study may provide potential input and help to 'operationalise' the Framework.

2.2 Expectations and question sets

The expectations that have been developed are presented in full in reference 3 for each of the ten themes, along with an associated discussion and commentary. Their coverage and potential use are illustrated here by considering the theme of 'reporting and learning'.

Expectations have been developed from each of these points. For example, the first two points in **Table 3** led to the following:

a) "There should be a systematic and effective process for the reporting of 'events', near-hits and non-conformance with the SMS which are relevant to process safety as an input to a wider operational experience (OE) programme. This should also apply to any contracting organisations. The reporting

Table 3. Major topics covered in the expectations of good practice relating to 'reporting and learning'

Ensuring a process for effective reporting
The need for a 'just' reporting culture
Obtaining the views of staff – including from team reviews
Using all relevant sources of data for developing learning
Ensuring a systematic process for investigation and follow-up
Achieving a well-resourced process for the review and dissemination of learning
Keeping learning 'alive' and in the 'corporate memory'
Incorporating learning into training
Ensuring effective follow-up actions and prioritising them
Maintaining learning during organisational change
Promoting leadership awareness of key learning
Use of event reporting as a potential key performance indicator (KPI)
Use of events to reinforce safety culture and to make the message 'realistic' to the workforce

process should be kept as straightforward as possible to ensure uptake."

b) 'Reporting should take place within a 'just' culture and should also be actively encouraged by management at all levels, even when the input may not provide 'welcome' news. Feedback should be given to those who report in order to reinforce commitment. It should be made clear that failure to report is unacceptable. Anonymity should be respected.'

Following the development of expectations under each theme, sets of 'penetrating diagnostic questions' have been developed based on the expectations. These will enable leaders, function heads and those involved more directly with operations to contribute to developing a critical perspective on resilience to failure and obtain a deeper understanding, whilst promoting a questioning approach as required in a strong safety culture. The question sets seek to identify the extent to which the expectations are embedded in organisational practice and include the need to examine examples of how the expectations are applied in practice.

They are designed to enable a flexible approach in identifying and prioritising areas for improvement. They can be applied either for all themes to obtain an overview, or in selected areas where concerns may exist. To enable this, each theme and associated questions have been made 'self-standing'; even though this results in some overlap in content. It is also anticipated that the expectations may evolve as a 'living' document, by incorporating findings from future events if these provide new insights.

2.3 Developing effective interventions

This section outlines the development of a modelling approach designed to enable duty-holders to develop effective improvement interventions. It takes account of the potentially complex interplay between engineered systems, structural, organisational, behavioural and cultural elements. Because of this complexity, unanticipated consequences of interventions are an important issue. The approach outlined below should help to minimise these and facilitate the development of more effective performance indicators.

A simple example, again based on 'reporting and learning', illustrates the concept. A technique known as Causal Loop Modelling (CLM) is used to depict the interactions between causal factors and the potential consequences of intended changes. It has the capacity to go beyond characterising simple linear causality to capture less immediately obvious, subtle, emergent or 'hidden' effects.

Figure 2 illustrates through a simple example how the approach can be used to analyse the possible consequences of actions intended to improve learning by increasing the number of 'events' being reported. The scenario considered is one where leaders recognise and promote the need to improve reporting and, following agreement with staff and their representatives, set in motion a programme to achieve this.

The arrows in **Figure 2** represent causality. An 'S' means a similar change is caused. An 'O' means an opposite change is caused. The right-hand loop shows that more reporting leads to more investigations and more corrective actions. Unless carefully controlled, prioritised and resourced, this may lead to a significant increase in workload and, in this scenario, the number of visible improvements and completed actions decrease because insufficient resources have been put in place to address the issues.

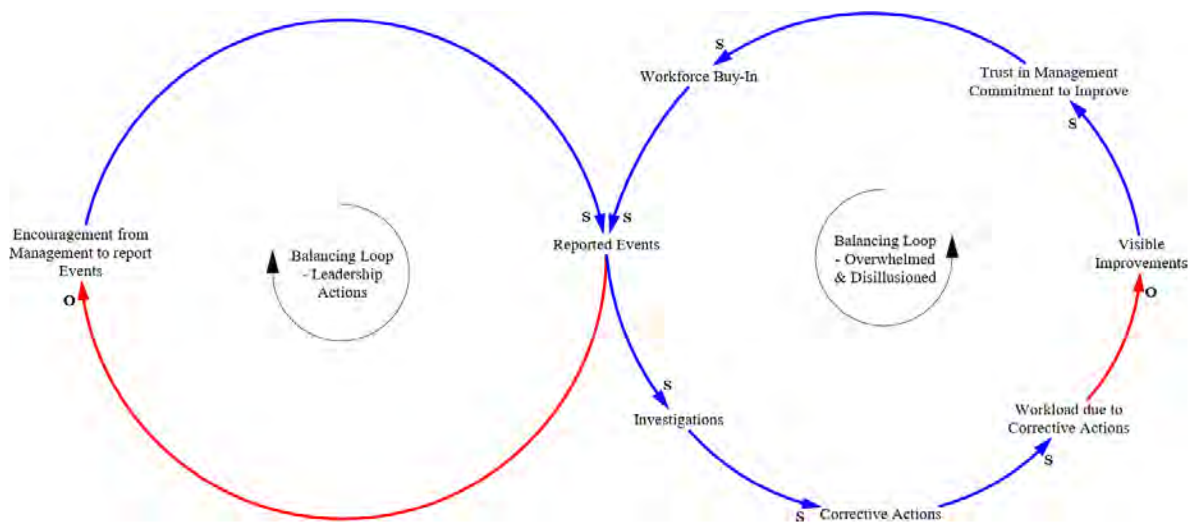

Figure 2 – Causal loop diagram presenting a simple example of how the approach can be used to analyse the possible consequences of actions intended to improve learning by increasing the number of 'events' being reported

A consequence is that staff see their best efforts to report leading to further actions on them and/or little material improvement. This understandably produces disillusion and cynicism within the workforce, which will then tend to reduce staff engagement and result in a lower level of reporting. More corrosively, its legacy may blunt the impact of future (different) initiatives and interventions. Meanwhile, leaders, having made a highly visible commitment, are still encouraging more reporting. This can lead to a situation where the workforce progressively loses trust in the ability of its leaders to understand operational 'reality'.

This example, although very simple, illustrates how a potentially worthwhile initiative might leave the organisation worse off than before it was launched. It is this capacity, to recognise potential pitfalls and perverse consequences at the design stage of interventions, that CLM is designed to address.

It also illustrates the importance of developing more effective performance indicators as a result of the modelling. Instead of a simple performance indicator, based on the number of events reported, other measures dealing with response and visible improvement would be important indicators.

In reference 3, more detailed examples are considered relating to a) contractor and supply chain management, b) safety culture and oversight, and c) incentives and performance indicators. The value of team working in constructing models is also discussed.

The example in **Figure 2** also illustrates how cognitive, behavioural and cultural factors can affect potential improvement activities within a complex system – in this case, degraded workforce commitment to safety because of a lack of visible response to their efforts and a growing dislocation between leadership aspirations and operational reality. In the events studied, a wide range of behavioural factors were identified as important contributors to failure and examples are given in **Table 4**.

Causal loop diagrams are now being developed to demonstrate how more effective interventions can be achieved across a sample of 'common' or 'archetypal' failure modes from the case study events. The modelling will (perhaps for the first time) include the potential behavioural responses which could undermine the success of proposed interventions.

In essence, the technique (or 'tool') will provide a risk assessment of the potential for vulnerabilities in the design and delivery of interventions.

Section 3: Discussion and transferrable learnings

By studying twelve major events across a range of high hazard industries, it has been possible to highlight the importance of organisational and cultural precursors. Identifying and addressing these important precursors offers a powerful way to minimise future events – including serious accidents, such as some of those studied. The events exhibited a high degree of commonality with respect to precursors to failure and findings have been synthesised and classified under ten themes, which may be of value in assessments and event investigations.

Many organisations have documented standards of good practice or 'expectations' which set out requirements for operations. The results of this analysis should enable them to 'benchmark' these against a 'model' set of expectations based on the findings from a wide range of actual events.

Table 4. Some examples of identified undesirable cognitive and behavioural issues

Development of shared 'mindsets'
'Conditioning' by past success
'Normalisation' of deviance
Lack of a questioning attitude
'Casual compliance' with procedures
Over-simplification and a failure to consider unintended consequences
Attitudes and behaviours driven by a commercial 'agenda'
Development of organisational complacency and 'drift'
A 'disconnect' between workforce and leadership expectations
Loss of understanding of operational 'reality' by leaders
Unintended reactions to 'incentives'

Sets of penetrating questions have recently been developed based on the expectations. It is envisaged that these should provide organisations with a practical means to assess the degree to which 'operational reality matches aspiration' and to identify where they may be most vulnerable. Application involves a flexible, team-based approach that can either cover all ten themes collectively or could be applied to particular areas where concerns exist. The approach should be of value to organisations across industry sectors and at different levels of capability and organisational maturity.

In the complex, interactive, socio-technical systems involved, developing effective improvement interventions is not straightforward. Making what might appear to be a simple improvement can produce unintended consequences unless the systems implications of the proposed change are carefully analysed and, importantly, behavioural factors which may adversely affect uptake are fully recognised and assessed. The use of causal loop modelling provides a valuable technique for assessing the potential impact of proposed interventions.

The ten themes and many of the associated findings underpinning the 'expectations' presented in this study appear to align strongly with those identified as important factors developed to 'build a more resilient future' in the wide-ranging SCS Framework (6). These are set out and discussed considering design and operation-time controls and exacerbating factors and the various layers of these (governance, management and task/technical). A possible area for further research would be to map the findings from the present study onto those in the framework and identify any new factors. The present study provides a potential systematic and practical approach to developing greater resilience in 'process safety' which might be considered in the further development of the SCS Framework and the 'common language' that it seeks to introduce.

Application of the present approach to other areas (such as healthcare and governmental preparedness) by examining its potential application to other case studies examined in the Engineering X project could be the subject of further research.

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Beyond the boundaries: characterising situational uncertainty in complex systems

By Dr Richard Judge, Shirin Elahi

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

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

Section 1: Background and introduction

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

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

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

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

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

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

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

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

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

Section 2: Analysis and insights

Complex systems failures: boundary issues

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

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

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

Beyond the boundaries: situational uncertainty

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

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

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

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

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

Characterising situational uncertainties

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

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

The myopic system

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

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

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

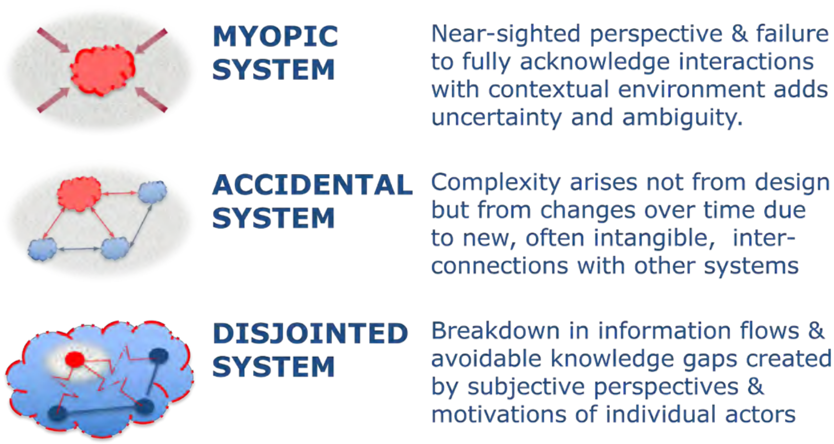

Figure 2: Typologies of boundary failures in complex systems

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

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

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

  While Natech accidents are often claimed as 'act of god' events, all too often they result from inadequate assessment or preparation for the challenging natural environments to which a plant may be exposed.[13] The investigation into Fukushima[14] concluded that it resulted from poor design assumptions, faulty decision-making and complacency that led to insufficient awareness of the obvious dangers of siting hazardous facilities on a tsunami-prone coast. It was described as an organisational and governance failure: "a profoundly manmade disaster—that could and should have been foreseen and prevented."

The accidental system

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

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

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

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

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

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

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

The disjointed system

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

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

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

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

Grenfell Tower fire in London in 2017.

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

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

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

Boundary issue: summary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Section 3: Discussion and transferable learnings

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

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

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

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

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

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

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

Table 1: Overview of system boundary issues

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

Appendix A: Tackling Situational Uncertainty

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

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

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

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

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

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

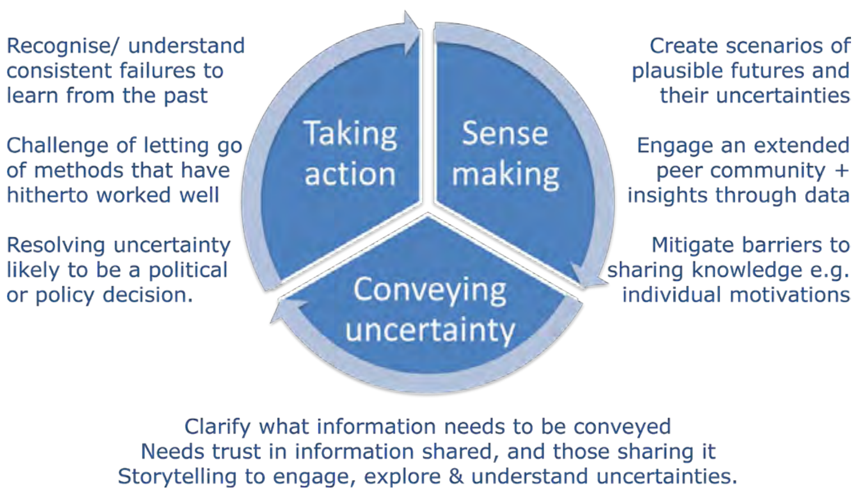

Figure 3: Tackling situational uncertainty

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

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

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Endnotes

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

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Chapter 3: Conclusion

What can we learn from the case studies?

Evidently, these case studies cover a wide variety of events, involving different complex systems, stakeholders, and geographies. Inevitably, many of the key takeaways, detailed in the individuals case studies (see Chapter 2: Case studies), will be specific to the context of the event. However, by reflecting on these case studies as a collection, with a cross-sector, multidisciplinary and global lens, we are able to draw some initial cross-cutting conclusions similar to those drawn by Judge and Elahi (in their case study), including:

- safety seen as an engineering or technology issue when in fact it was a cultural or social one
- treating complex, uncertain issues, and risk with tools developed for complicated ones
- a lack of systemic thinking and action over the lifetime of the systems
- unverified assumptions
- inconsistent and poor data management to support statistical analysis and modelling
- little or no attention to the structure of governance early in a project
- ill-defined boundaries of responsibility, authority, and accountability
- lack of alignment of purpose between actors
- poor information sharing in the face of a blame or project driven culture.

Reflecting further on the evidence base and these initial conclusions, several common lessons from those case studies relating to engineering infrastructure are elaborated below. We note that it is likely possible to extract many other lessons learned from these case studies by different people considering them through different lenses, and we encourage readers to do just that as well as to reflect on how these learnings may apply to their own professions, disciplines, sectors, geographies and social contexts.

Risk and uncertainty

John Kay and Mervyn King, in a recent book,[1] argue that western political systems "crave certainties which cannot exist and invent knowledge we cannot have" in an attempt to put numbers to uncertainties. They stress the difference between a risk assessment of a known process and managing Knightian uncertainty.[2] This "craving" manifests itself in safety management systems, for example, the UK Network Rail system,[3] examined in several case studies, being one of many:

> *"The Safety Risk Model (SRM) provides a network-wide risk profile for the GB railway. It has underpinned the industry's evidence and risk-based approach to safety management for the best part of two decades. It provides a trusted starting point for quantified risk analysis.*
>
> *RSSB uses the model to produce risk estimates for 131 hazardous events and almost 3,000 event precursors. The SRM measures risk in terms of frequency, how often we expect something to occur, and consequence, the expected level of harm that arises when it does. Risk is presented in units of Fatalities and Weighted Injuries (FWI) per year."*

This approach, evolved from the predictability of failures of early electronic systems,[4] assumes a static world in which the safety engineer has an omniscient understanding of all possible risks and their likelihood. Unfortunately, such omniscience does not exist in the messy, interacting systems in the real world. Despite this, regulatory systems often reinforce this trend by requiring bodies creating a hazard to demonstrate they have reduced the risk to "as low as reasonably practicable" where *practicable* includes a financial criterion based on the estimated probability of harm and the cost of potential mitigation.[5]

An interesting example of uncertainty is the 2011 Brisbane flood (case study by Punzo), exacerbated by the mismanagement of the Wivenhoe dam and its associated smaller dams which amplified the impact of the flood. The dams serve two conflicting purposes – to store water to prevent dry-season water shortages and to restrict the flow to prevent floods during wet-season storms. Politicians had to balance these demands: with an unpredictable storm forecast, they could have lowered the water levels in the dams but, with an unknowable dry season ahead, they needed to keep sufficient water to prevent drought. Statistics can provide trends over many decades, but they are not able to predict what *will* happen later this year. This requires a decision-making process that does more than balance calculated probabilities, for which "the system" was unprepared.

Statistics

Before tyre pressure monitoring was introduced, an estimated 414 fatalities occurred annually in the US due to flat tyres or blowouts.[6] With this number of incidents, it is possible to plot trends, investigate the safety performance of different types of tyre, undertake failure mode analysis, and so on, and work out the value of prevented fatality (VPF) for possible improvements.

On GB mainline railways since 2003, there have been an average of 1.3 fatalities annually (excluding suicides, trespassers, and level crossing users).[7] Of these, none could be attributed to wheel failure. But this is not to say that the risk of wheel failure can be ignored. On 3 June 1998 at Eschede in Germany, a wheel failure resulted in an accident which killed more than 100 passengers. It could have been described as a statistical outlier, but it is more relevant to say that there simply wasn't enough information to make any meaningful calculations. Attempting to apply statistics where there are inadequate data can be deceptive. This is particularly the case for nuclear accidents. Three Mile Island, Chernobyl, and Fukushima (discussed in Taylor et al.'s case study) were all "one offs" and were related to specific design features; they do not provide data that can readily be used in risk assessments of other designs.

Creeping aggravating factors

Many complex systems include long-lasting infrastructure. There is a natural tendency to undertake a full safety analysis when the project is new and to roll-over the conclusions for future years. The case study of transport network resilience in Australia by MacAskill et al. showed how this can be dangerous. Climate change is making rainy seasons wetter and dry seasons drier, thus making dam management more challenging. This is exacerbated by population growth, placing more demands on storage for the dry season, and building on flood plains, reducing the options for uncontrolled discharge in storm conditions.

A similar problem was identified in Taylor et al.'s case study discussing the 2006 Nimrod plan crash.[8] The plane had been operating for several years and staff involved made the unvalidated assumption that the outcome would be that everything was fine, despite the modifications made in a hurry before the Falklands war.

In the Dutch DELTA programme (case study by Judge & Petersen), the 1953 *watersnoodramp* (flood disaster), with more than 1,800 deaths, led to a major rethink of coastal defences, weather prediction, and warning systems. This was the incentive for a 40-year programme of building flood defences. However, almost before it was complete, there was the realisation that higher storm surges, higher rainfall and fiercer winds caused by the changing climate would overtake the calculations on which much of the infrastructure was based. This led to the development of adaptive management practices as a way of dealing with uncertainty, with these methods having direct relevance to planned adaptive regulation (PAR) and other anticipatory governance frameworks. Adaptive methods offer considerable potential as a way of tackling significant uncertainties – such as those arising from rapidly advancing innovations or from multi-decade time horizons.

Business culture

Several case studies raised the importance of the culture in and around a workplace to the safety of users. The Public Private Partnership contract with Edinburgh Schools Partnership Limited (ESP), discussed in Gosling et al.'s case study, referenced insights into a general problem of the interweaving failures in unvalidated assumptions regarding complexity, minimum building standards, quality culture, oversight, and commercial drivers established during early phases of the project.[9] The official report stressed the need a culture change through education and training to ensure that people with safety roles fully understood and accepted their responsibilities.

A similar comment was made in the official report into the Hatfield train crash (case study by Kemp), which noted at least one person with a safety role who appeared to have been unconcerned that did not understand the basic technology he was supposed to be monitoring.

The case study by Taylor et al. noted a dozen different accidents identified what it described as the 'Business Environment' (e.g. the need to complete a project to a very tight schedule or the impact of major organisational change on operations), which led to significant unintended consequences in most of the events studied. It also noted several common cultural issues that contributed to accidents:

- a lack of commitment and operational awareness among leaders;
- a tendency towards 'operational drift' where poor practices become the norm;
- the absence of a sufficiently questioning attitude and 'precautionary' approach to emerging risks and rigour in addressing them;
- failure to involve the workforce in identifying and implementing improvements.

The case study by Kuo & Vassalos on a Ro-Ro accident in Belgium came to similar conclusions – that the attitude of people (business culture) was an important determinant of accident risk.

Governance

Inadequacies in governance were highlighted as a key factor in several case studies. This is hardly surprising as many important decisions, such as how much to spend on flood defences or how to implement virus testing, are 'delegated upwards' to politicians who balance the conflicting demands for action to mitigate a potential crisis with national budgets, public opinion, political dogma, and many other priorities.

The short-term nature of most political decision-making presents a particular challenge when addressing long term issues such as those faced by the 40-year Dutch DELTA flood protection programme (case study by Judge & Petersen). How do governmental decision-makers ensure that their successors do not abandon or undermine their efforts due to short-term electoral pressures or changing priorities?

Sometimes political objectives, such as privatisation or cost reduction, can override mechanisms to control risks. The Hatfield derailment (case study by Kemp) was an example of a situation where restructuring the industry had made almost impossible collaboration and hazard reduction trade-offs at the design stage.

But the most serious governance issue is that legal and regulatory structures, designed for simple systems with a single *duty holder* having clearly defined responsibilities, are inadequate to manage the risks of a sprawling complex system with many different unconnected actors, all with different priorities. This is demonstrated, in simple terms, in the case study of the Bexley train crash by Elliott – an accident with three independent causes – but there are many more complex systems.

Bridging the gap between traditional and unconventional practice

While two of the case studies (one by Elliott and one by Kemp) analyse historical train derailments, two others (one by Tomlinson and one by Haddock & Beckford) examine current approaches to safety management, in the UK. The latter two provided an opportunity to reflect on transitions from traditional to unconventional practice.

A Systems Approach to Reducing Train Accident Risk by Tomlinson describes the traditional methodical approach to risk assessment and reduction in use for some time by the rail industry. *Understanding and Utilising Data for a Seasonally Agnostic Railway* by Haddock & Beckford, drawing on the fatal accident at Carmont in 2020 as a representative weather-related incident, proposes a new systemic model of the interactions of weather events, railway asset specification, and railway asset maintenance rooted in a cybernetic understanding.

The two approaches are radically different. Tomlinson offers a pathway to railway engineers through which failure risk can be identified, analysed, the costs and benefits of solving it noted, and the business case produced for priorities to be set. Brian & Haddock seek to identify emergent risk, including time, space and interdependence, and provide information for anticipatory and preventative action.

The Tomlinson case study represents, at the time of its writing, the state of common contemporary practice regarding the approach to, and processes of, risk management and valuing of risk and consequence. It presents a model for pricing and prioritising individual asset risk, demonstrating how the industry has measured and evaluated risk (and reduction of risk) over time and communicated to stakeholders how those characteristics which are measured have been improved. The basis of this approach is that all hazards are identifiable, the risks posed can be quantified and a rational decision made about how much should be spent on mitigating each. Although the case study is systemic in concept, the method described is largely systematic rather than embodying a strictly systemic lens. Such nuance highlights how relatively narrow definition of system boundaries and linear behaviour delineation in systematic approaches may fail to capture emergent risks from the dynamic interaction of interdependent elements comprising a system and that system with its environment; that is, exposure to Black Swan events or the Swiss Cheese Effect.

The shift to the seasonally agnostic railway model (SARM) in Haddock & Beckford's case study is profound. It treats the railway as a dynamic, complex system, and embraces interactions and interdependencies in such a manner as to identify the impact of adverse weather events on the performance of the system. It is explicitly addressed to systemic performance risk expressed in terms of the impact on the passengers (Your train will be delayed by 'x'). Additionally, it employs available data about the condition of the railway in the context of anticipated weather events to dynamically identify (in impact order) those assets which appear vulnerable to such events, enabling a strategy of 'predict and prevent' to be employed.

The contrast between these two case studies highlights significant differences in interpretation of the 'complex systems' and the application of different modes of systemic inquiry informed by different observational perspectives. There are two dominant considerations in this.

The first is the realisation that the mechanistic thinking that necessarily underpins the technical operation of the 'machine' that we call the railway also pervades the management thinking and therefore the approach to risk management; we think that way because that is the way we think, it is internally focused and self-referential, closed off to systemic reflection, learning, and adaptation.

The second realisation is that the SARM starts with a fundamentally different assumption – that the railway is an adaptive, complex system, that learning must be embedded in its information architecture and, importantly, that the primary and mechanistic considerations of risk can be embraced in a manner that will highlight their adequacy (or not). SARM assumes that managing the railway as a dynamic system is different, systemically, to engineering the railway as a machine. OUR assumption is that the standard engineering has already delivered a risk-mitigated infrastructure so we can consider internal factors (maintenance standards), external factors (adverse weather) and interdependency factors (expected weather versus specification) which may compromise performance (adherence to timetable).

The SARM approach is possible because of changes in our understanding of how we can employ emerging technology and thinking to capture data and develop whole organisational models and simulations of key interactions, a capability that did not exist when common contemporary approaches were developed.

Frameworks for analysis

Case study authors were asked to reflect on the extent to which the *The York Framework* (see Figure 3 in Chapter 1) was appropriate for their study. In many instances, particularly those involving engineered systems, the framework provided an adequate structure by itself. By contrast, the case study of the network of creative and empathetic citizens attempting to alleviate to crises in Chilean society (case study by Rojas), discovered issues that could not be readily fitted into *The York Framework* and so the team also used the Social Emergence Paradigm (SEP) framework. *The York Framework* allowed the characterisation of the complex system and the SEP allowed focus on the different layers of the complex system for achieving successful outcomes. This highlights that, given the nature of complex systems, we must remain cognizant that a single framework is unlikely to be perfectly deployable for all analyses of all complex systems and related success or failure events. We must remain open and adaptable to challenges and new approaches for examining complex systems.

Where to from here?

These case studies provide a new body of information on successes and failures of complex systems, offering readers the opportunity to explore, and exploit based on evidence, how the design, construction, operation, management, and governance of complex systems may result in safe or unsafe outcomes.

We hope that engineers and other professionals—including but not limited to policymakers, plumbers, asset owners, electricians, lawyers, construction managers, financiers, and users—will reflect on the entire collection of case studies, not just those of direct interest, to maximise the potential for transferable learnings across profession, discipline, sector, and geography. We each individually interact with, and within, complex systems every day, and it is becoming ever more important that practitioners and users working on and with critical infrastructures are aware of the far-reaching impact of technical and nontechnical decision-making throughout their lifecycle.

We encourage individuals, universities, professional institutions, government, and intergovernmental organisations and businesses to leverage this content as an educative tool. The Engineering X, Safer Complex Systems mission intends to further develop, and build from, this case study content. This will include innovative education tools to influence engineering education as well as supporting advocacy and exploring novel governance solutions towards safer complex systems. Convening diverse communities is a critical strand of our work, as only through collaboration will we be able to safely navigate and manage the complex challenges of the present and future. We invite proposals of what should be in our programme of activities moving forward.

Finally, the Safer Complex Systems mission is complex and evolving in nature itself, as were these case studies. We are continuously learning, challenging our own approaches and adapting our strategy and programme of activities, and these case studies have provided a foundation for evolving further. If you would like to join our community or make proposals, please get in touch with our team or join our LinkedIn Community of Practice.

Summary

Safety is a multi-dimensional concept comprising attributes of qualitative and quantitative nature and, as such, it is difficult to address each and every component, compute all contributions and provide an absolute and well determined answer. It also varies in time so whilst aiming at targets that have utility, their context can vary due to human/societal perception which in turn are related to attitude, behaviour, experience and culture. There is therefore a need for a methodology to govern and manage safety that enables continuous refinements whilst incorporating feedback from practice and scientific/engineering advancements. The complexity that is embedded in and intrinsic to the functionality of most modern engineering systems makes such a task even more painstaking and challenging.

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